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Application of LIMB to Pulverized Coal Boilers A Systems Analysis: Limestone Feed and Boiler Systems

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APPLICATION OF LIMB TO PULVERIZED COAL BOILERS - A SYSTEMS ANALYSIS

Limestone Feed and Boiler Systems

by

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The report gives results of a systems snalysis of the application of Limestone Injection Multistaged Burner (LIMB) technology to pulverized-coal boilers. It evaluates alternative limestone handling, preparation, and injection methods and boiler system impacts associated with LIMB applications. LIMB simultaneously reduces sulfur oxides (SOx) and nitrogen oxides (NOx) emissions from pulverized-coal boilers. It is based on using low-NOx combustion techniques combined with dry limestone injection into the furnace for simultaneous SOx control. The major aim of the study was to evaluate alternative concepts for application of the technology assess potential system problems related to its application, and identify engineering solutions to those problems. Further goals were to identify information needs related to technology application and recommend evaluations to acquire this information. Conceivably, all new boilers could be designed to handle any foreseeable impacts associated with LIMB; however, the practicality of LIMB as a retrofit technology depends on its compatibility with existing boiler systems. Sufficient information is not yet available to accurately gauge its applicability as a retrofit technology; however, this study identified potential system impacts, situations where the impacts will likely be minimized, and design or operating procedures for dealing with them.

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Coal	Nitrogen Oxides	Stationary Sources	21D	
Combustion		Limestone Injection	21B	
Limestone		Multistage Burners	08G	
Burners			13A	
Feeders			13I	

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ABSTRACT

This interim report presents results of a systems analysis of the application of Limestone Injection Multistaged Burner (LIMB) technology to pulverized coal boilers. This study was conducted as part of a larger U. S. Environmental Protection Agency program to develop the LIMB technology. This report specifically evaluates alternative limestone handling, preparation, and injection methods and boiler system impacts associated with LIMB applications. Particulate control system impacts are not addressed in this report.

LIMB is a technology designed to simultaneously reduce sulfur oxides (SO_x) and nitrogen oxides (NO_x) emissions from pulverized coal boilers. The technology is based on the use of low NO_x combustion techniques in combination with dry limestone injection into the furnace for simultaneous SO_x control. The major objective of this study was to evaluate alternative concepts for application of the technology, assess potential system problems related to its application, and identify engineering solutions to those problems. Further goals were to identify information needs related to technology application and recommend evaluations to acquire this information.

Conceivably, all new boilers could be designed to handle any foreseeable impacts associated with LIMB. However, the practicality of LIMB as a retrofit technology depends on its compatibility with existing boiler systems. Sufficient information is not yet available to accurately gauge its applicability as a retrofit technology. However, this study identified potential system impacts, situations where the impacts will likely be minimized, and design or operating procedures for dealing with them.

Depending on coal type and boiler system design, major problems potentially arising from LIMB applications include increased furnace slagging, convection pass plugging, overloading or plugging of ash removal systems, and reduced combustion efficiency. If not severe, these problems can be dealt with through alterations in boiler operating procedures or minor system design modifications. No major problems are expected with application of limestone handling, preparation, and injection equipment other than space limitations at some existing facilities. Several potential limestone processing schemes are possible, any one of which could prove best for a particular application.

Applications where LIMB appears most compatible with the existing boiler system are those which fire low rank coals. In these applications, the coal properties and boiler system design both appear well suited for LIMB. System impacts will be larger with bituminous coal units because of larger coal sulfur contents and less conservative system designs. Also, bituminous ash chemistry is such that limestone injection may increase furnace slagging and convection pass plugging. The extent of these problems is unknown and further research is recommended.

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LIST OF ABBREVIATIONS AND SYMBOLS

Numerous abbreviations and symbols, some of which may be unfamiliar to the reader, are used throughout this report. Those used infrequently are generally defined where used. Others are generally defined when they first appear but may not be defined elsewhere in the report. Thus, for the readers convenience, the following list of abbreviations and symbols which are used relatively frequently is provided.

In a very few cases a given symbol or abbreviation may have more than one meaning within the report. When this occurs, specific definitions are provided within the report which override the general definitions in this list.

ABBREVIATIONS

BMI -- ball mill index
Btu -- British thermal units
°C -- degrees Celsius
CFM -- cubic feet per minute
cm -- centimeter
DMB -- distributed mixing burner
°F -- degrees Fahrenheit
FEGT -- furnace exit gas temperature
ft -- feet
g -- gram
gpm -- gallons per minute
HGI -- Hardgrove grindability index
HHV -- higher heating value
HP -- horsepower
in -- inch
J -- Joule
kg -- kilogram
kPa -- kilo Pascal
kW -- kilowatt
kWh -- kilowatt hour
lb -- pound
LIMB -- limestone injection multistaged burner
m -- meter
Mg -- megagram
Mohs -- a material hardness scale
MW -- megawatt (usually electric unless otherwise defined)
$\mathrm{MW_e}$ -- megawatt electric
$\mathrm{MW_t}$ -- megawatt thermal
ng -- nanogram
Pa -- Pascal

psi -- pounds per square inch
RPM -- revolutions per minute
TPY -- tons per year
WI -- Bond work index

SYMBOLS

Al -- aluminum
Ca -- calcium
Fe -- iron
K -- potassium
Mg -- magnesium
Na -- sodium
NO_x -- nitrogen oxides
O -- oxygen
P -- phosphorous
S -- sulfur
Si -- silicon
SO_x -- sulfur oxides
Ti -- titanium
ΔP -- pressure drop
μ -- micron

The above symbols which represent elements may appear singly or combined with other symbols to represent compounds.

SECTION 1

INTRODUCTION

This interim report presents results of a systems analysis of the application of Limestone Injection Multistaged Burner (LIMB) technology to pulverized coal boilers. This study, conducted by Radian Corporation, is sponsored by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, North Carolina and is part of a larger EPA program to develop the LIMB technology. The goal of this study is to conduct an overall systems analysis of LIMB technology applications. This report specifically evaluates alternative limestone preparation and injection methods and boiler system impacts.

This section of the report presents a description of the overall EPA sponsored LIMB program with emphasis on how this study fits in. It also discusses background rationale for development of the technology. Finally, it describes the focus and organization of this report.

DESCRIPTION OF LIMB PROGRAM

The LIMB program is an effort to develop an effective but inexpensive emission control technology for pulverized coal boilers that will simultaneously reduce sulfur oxides (SO_x) and nitrogen oxides (NO_x) emissions. The technology is based on the use of low NO_x combustion techniques in combination with dry limestone injection into the furnace for simultaneous SO_x control.

The LIMB Program was initiated in fiscal year 1981 based on the results of earlier studies conducted on low NO_x combustion techniques and dry sorbent injection. The multiyear program is planned to result in a complete technology design package. To accomplish this objective EPA has initiated research and development activities including fundamental studies and bench- and pilot-scale experiments.

The goals of the fundamental work are (1) to establish the principal mechanism of sulfur capture with LIMB, and (2) to develop kinetic data needed to provide a sound technical basis for evaluating and developing the technology. The goals of the bench-scale work are to identify and understand the phenomena which are key to simultaneous SO_x/NO_x control. This is being done in small bench-scale equipment which allow examination of a range of parameters under controlled conditions. The goal of the pilot-scale work is to evaluate LIMB performance with realistic burner sizes more comparable to full size units.

Along with these research activities EPA also initiated a systems analysis task of which this interim report is a product. A major objective of the task is to evaluate alternative concepts for application of the technology on pulverized coal boilers, to assess potential system problems related to its application, and to identify engineering solutions to those problems. This includes analyses of alternative limestone preparation and injection schemes, boiler system impacts associated with LIMB, and impacts on downstream emission control systems. Additional goals are to identify information gaps related to the assessment of system impacts and to recommend studies or experiments to acquire the needed information.

TECHNOLOGY DEVELOPMENT RATIONALE

The need for effective low-cost techniques for control of SO_x and NO_x emissions has become apparent in recent years because of increased public awareness of the problems associated with acid rain. The long-range transport and transformation of SO_x and NO_x are believed to be major factors contributing to acid rain formation. However, these pollutants also degrade local air quality, present health hazards, and participate in photochemical smog formation. To address these problems, effective low-cost control techniques are needed that are applicable to both new and existing sources of these pollutants.

Coal consumption is a major contributor to SO_x and NO_x emissions in the United States today. Major users of coal include large industrial and utility boilers. Recently published data show that utilities alone accounted for about 81 percent of the total 1980 U. S. coal consumption.[1] Coal consumption by electric utility boilers has increased substantially over the past ten years, especially in the western U. S. This trend is shown rather dramatically in Figures 1-1 and 1-2.

The majority of large capacity coal units, those greater than 73 MW_t (thermal input) (about 200,000 lb steam/hr), are pulverized coal boilers. Current U. S. regulations limit SO_x and NO_x emissions from new utility boilers constructed since 1978 in this size range. NO_x emissions are limited to 210-260 ng/J (0.5-0.6 lb/million Btu) and 70-90 percent control of SO_x emissions is required. Emissions from other industrial and utility boilers above 73 MW_t and constructed after 1971 are also limited, though less stringently. However, there is a large population of coal-fired boilers built before 1971 which are subject only to state standards. These units are often regulated much less stringently than new units and represent a major source of SO_x and NO_x emissions.

The use of coal as an energy source is likely to continue to increase significantly in the future. This increased use will cause increases in SO_x and NO_x emissions in spite of current regulations affecting new sources. Thus, if substantial SO_x and NO_x reductions prove to be necessary to control acid rain or to address other local or regional concerns, additional control will be needed for existing as well as new emission sources.

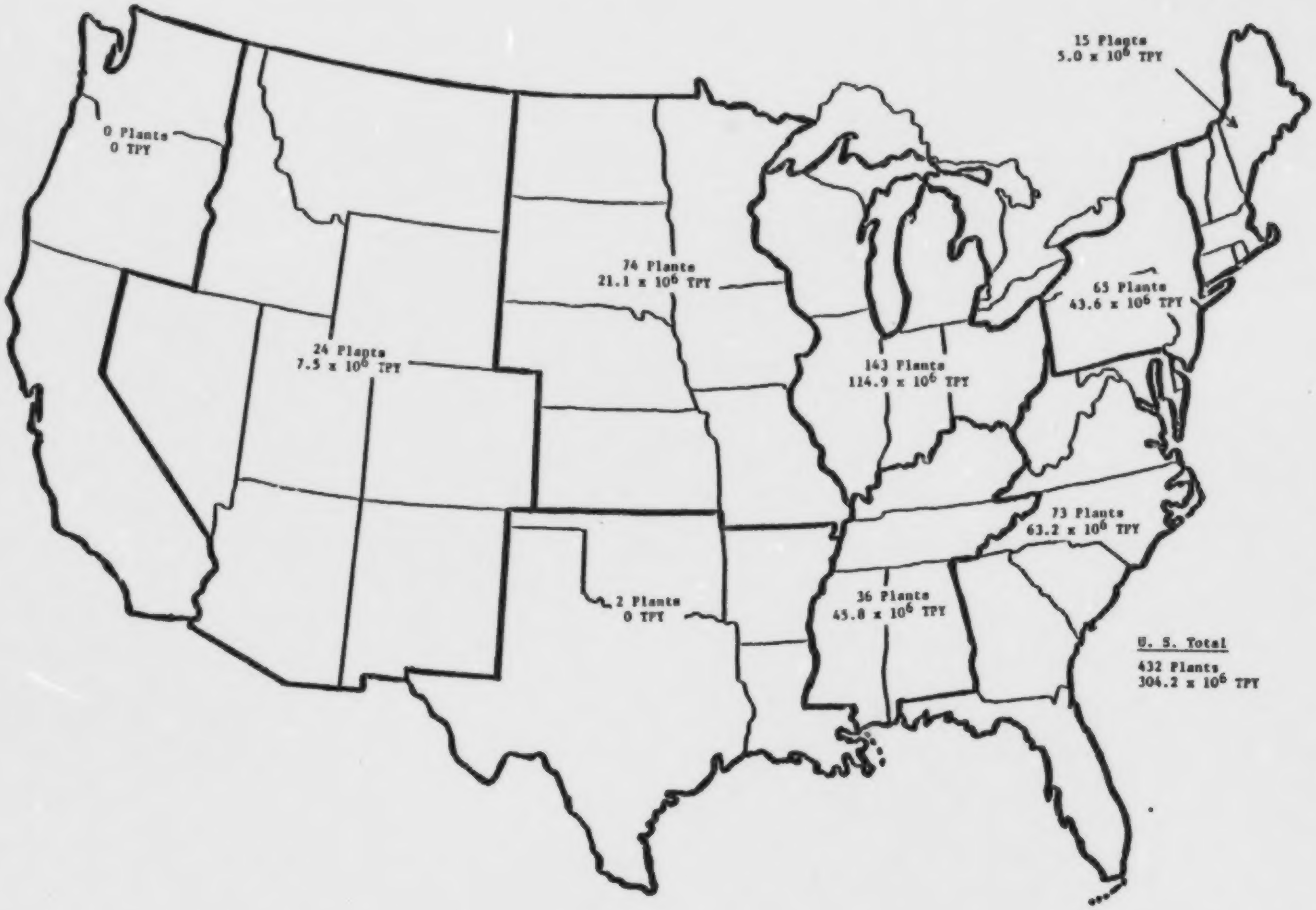
0 Plants
0 TPY
24 Plants
7.5 x 10^6 TPY
74 Plants
21.1 x 10^6 TPY
2 Plants
0 TPY
143 Plants
114.9 x 10^6 TPY
36 Plants
45.8 x 10^6 TPY
73 Plants
63.2 x 10^6 TPY
65 Plants
43.6 x 10^6 TPY
15 Plants
5.0 x 10^6 TPY
U. S. Total
432 Plants
304.2 x 10^6 TPY

Figure 1-1. United States coal fired steam electric plants and coal consumption by region, 1969.[a,b]

[a] Compiled from data presented in reference 2. Only plants greater than 25 MW_e (megawatt electric) included.

[b] To convert to Mg/yr (megagrams per year) multiply TPY (tons per year) by 0.907.

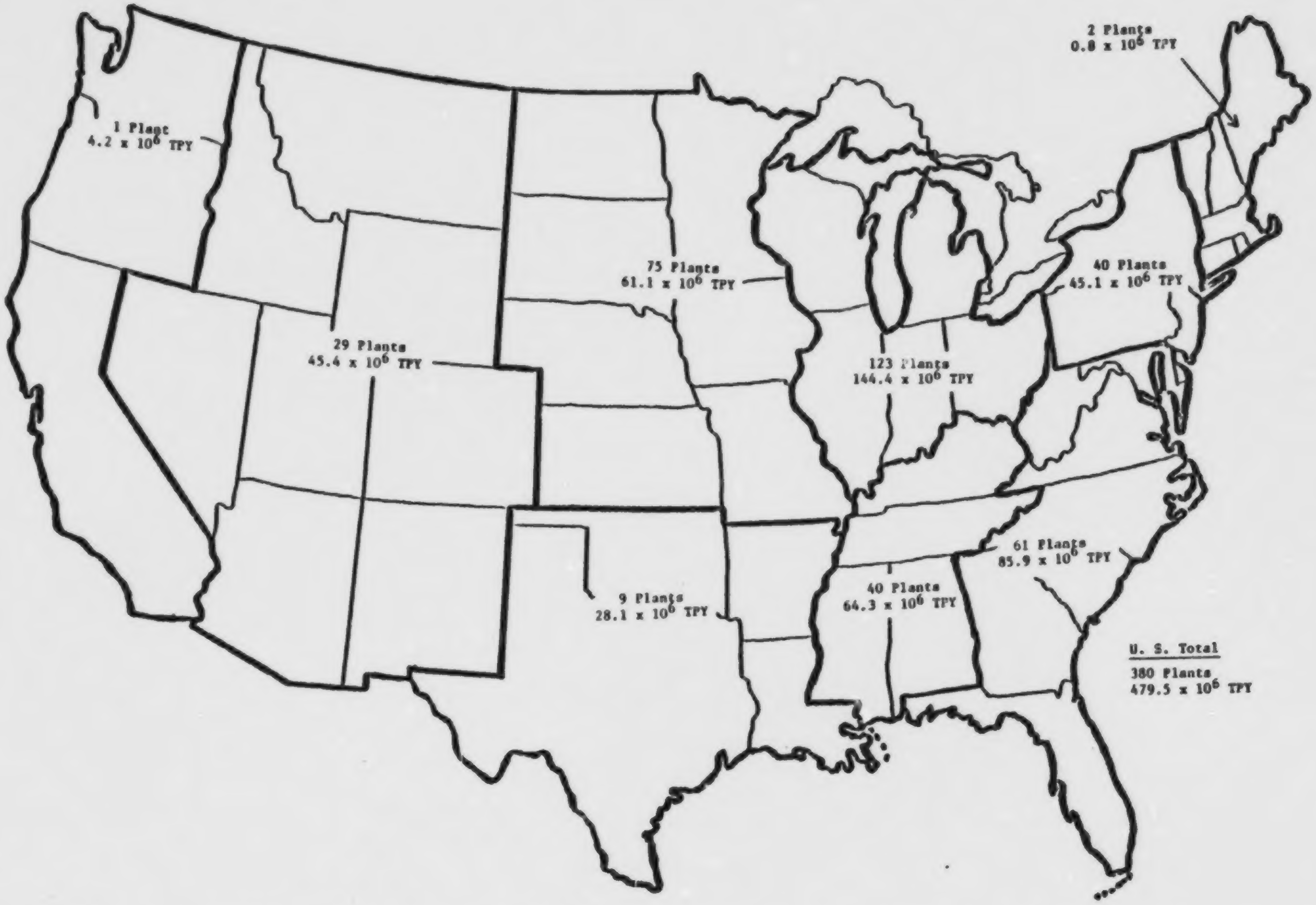
2 Plants
0.8 x 10⁶ TPY
1 Plant
4.2 x 10⁶ TPY
75 Plants
61.1 x 10⁶ TPY
40 Plants
45.1 x 10⁶ TPY
29 Plants
45.4 x 10⁶ TPY
123 Plants
144.4 x 10⁶ TPY
61 Plants
85.9 x 10⁶ TPY
9 Plants
28.1 x 10⁶ TPY
40 Plants
64.3 x 10⁶ TPY
U. S. Total
380 Plants
479.5 x 10⁶ TPY

Figure 1-2. United States coal fired steam electric plants and coal consumption by region, 1978.[a,b]

[a] Compiled from data presented in reference 3. Only plants greater than 25 MW_e (megawatt electric) included.

[b] To convert to Mg/yr (megagrams per year) multiply TPY (tons per year) by 0.907.

Section 6 - Limestone Handling and Preparation
presents background information on limestone handling and preparation to serve as a basis for the evaluations in Section 7;

Section 7 - Alternative Injection Schemes
presents evaluations of alternative limestone preparation and injection methods;

Section 8 - Boiler Design and Operation
presents background information on boiler design and operation to serve as a basis for the evaluations in Section 9; and

Section 9 - Boiler Injection Impacts
presents evaluations of the impacts of LIMB on the boiler system and assesses potential impacts of boiler design on the performance of LIMB.

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1. U. S. Department of Energy. Coal Consumption-Bituminous Coal, Lignite and Anthracite. Monthly Energy Review, 81(12):60, December 1981.

2. National Coal Association. Steam-Electric Plant Factors, 1970. 20th edition. Washington, D. C., 1970.

3. Lin, K. and J. Dotter. Steam Electric Plant Factors, 1979. 29th edition. National Coal Association, Washington, D. C., 1979.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

This study evaluated system impacts associated with LIMB applications to pulverized coal boilers. Specifically addressed were the limestone feed and boiler systems. This section presents conclusions concerning LIMB applications based on the results of these evaluations. Also presented are recommendations about information needs to better define system impacts and further develop LIMB technology.

CONCLUSIONS

Conceivably, all new boilers could be designed to handle any foreseeable impacts associated with LIMB. However, the practicality of LIMB as a retrofit technology depends on its compatibility with the existing boiler system. Specifically, technology application should not require major boiler design modifications or severe boiler operation impairments. LIMB is still under development so sufficient information is not yet available to accurately gauge its applicability as a retrofit technology. However, this study identified potential system impacts associated with LIMB, situations where these impacts will likely be minimized, and design or operating procedures for dealing with these impacts.

The major factors influencing the compatibility of LIMB appear to be the coal properties and designs of the boiler furnace, convection section, and ash removal systems. Depending on these factors, potential problems arising from LIMB applications include increased furnace slagging, plugging of tight convection section passes, overloading or plugging of ash removal systems, and incomplete coal combustion. If not severe, these problems can be dealt with through alterations in boiler operating procedures or minor system design modifications.

No major system problems are expected with application of limestone handling, preparation, and injection equipment other than potential space limitations at some existing facilities. Limestone feed systems will have to handle limestone feed rates of about 10 to 30 percent of the coal feed rate. Several, potential limestone preparation and injection schemes are possible which would allow injection through the burners, secondary or tertiary air ports, or other ports installed on the furnace walls. Any one of these schemes could prove best for a particular application depending on SO_2 control considerations and the existing coal feed system design. Not much data are available on the dry grinding characteristics of limestone but measurements of limestone properties should insure adequate limestone feed system design.

Applications where LIMB appears most compatible with the existing boiler system are those which fire low rank coals. In these applications, the coal properties and designs of the furnace, convection section, and ash removal system all appear well suited for LIMB.

However, system impacts will be larger with bituminous coal units. Bituminous coals generally have higher sulfur levels than lower rank coals, and hence require injection of larger quantities of limestone. This affects the size of the limestone handling, preparation, and injection equipment; boiler slagging and fouling tendencies; ash removal requirements; and downstream particulate control requirements. Greater limestone injection rates not only require larger limestone feed system capacities and result in larger feed system power requirements, but also tend to increase boiler thermal losses. Limestone injection in these units results in larger ash loadings handled by the boiler and ash removal systems and may increase the tendencies for furnace slagging and convection pass fouling and erosion.

The potentially most critical problem of those mentioned above concerning the application of LIMB technology to bituminous coal units is that of interactions between limestone and ash particles. These interactions may result in decreased ash fusion temperatures which, together with the increased ash loadings, may cause increased furnace slagging and plugging of the convection passes. This effect is not likely to occur with low rank coals due to differences in ash chemistry. Another related problem is that many older bituminous coal units remove economizer ash with wet sluicing systems. With LIMB, this ash will contain large quantities of calcium and sulfates. When exposed to water it will likely exhibit cementitious properties causing plugging of sluicing systems. Wet sluicing systems for economizer ash are not typically used on units firing low rank coals.

Thus it appears that LIMB will be most easily retrofit on units firing low rank coals. However, about 75 percent of the existing boiler population on a total capacity basis was designed to fire bituminous coal. Further, bituminous coal units account for an even larger percentage of existing SO_x emissions. For these reasons, LIMB must be applied to bituminous coal units in order to have a large impact on existing SO_x emissions. In this study, some potential problems were identified concerning the application of LIMB to bituminous coal units. Further evaluations are needed to define the magnitudes of these problems and to engineer solutions to them. Some specific recommendations are discussed below.

RECOMMENDATIONS

Recommendations from this study are discussed below under separate subheadings. The first concerns research and development activities that should be undertaken in order to better understand and respond to system impacts associated with the application of LIMB technology. The second concerns additional engineering analyses which would further define system impacts and problems, engineering solutions to those problems, and the compatibility of LIMB with the existing boiler population.

Research and Development Needs

Several research needs related to the limestone feed and boiler systems were identified in this study. These include measurements of the impacts of LIMB on boiler slagging and fouling tendencies, ash entrainment, ash physical properties, and convection section erosion; and measurements of limestone grinding characteristics.

The most critical research need is to determine the effect of LIMB on slagging and fouling - especially in bituminous coal units. Limestone injection tests in some bituminous coal units have resulted in severe deposit buildup and plugging in the convection passes. This buildup could result from a combination of increased solids flow, reduced ash fusion temperatures, and tight tube spacings. Some reports from these tests indicated that the deposits were sticky at normal gas temperatures but became friable when cooled, indicating that the ash melting properties were important.

Correlations of ash fusion temperatures with composition and various slagging indices are available to predict the effects of increased calcium content on ash slagging tendencies. Also, direct laboratory measurements have been made of the impacts of increased levels of limestone on the fusion temperatures of ash-limestone mixtures. For example, Combustion Engineering recently made a series of such tests in an EPRI sponsored limestone injection study.[1] However, these types of tools or tests presume 100 percent interaction between the ash and injected limestone particles. None of them model the dynamics of limestone-ash interactions in the furnace. The true extent of interaction is unknown, but is probably related to the conditions under which the limestone and ash particles come into contact.

As a result, bench- or pilot-scale tests should be conducted in which limestone particles are injected into a furnace operated so that a variety of peak flame temperatures and time-temperature relationships occur. These tests should include injection through the burners and through ports located at other furnace temperature zones. Air cooled probes can be placed downstream in various temperature zones reflective of radiant and convection sections in order to measure ash deposition rates. Also, various ash strength and friability tests can be conducted on the deposited samples. The tests should be conducted for a variety of coal types and limestone injection rates. Some similar tests have been conducted at the DOE Grand Forks Energy Technology Center[2] with low rank coals and by Babcock and Wilcox[3] with bituminous coal. But these tests involved conventional burners and relatively low limestone injection rates.

Other research objectives should include measurements of the influence of LIMB on total ash entrainment and ash physical properties since these factors can influence ash removal system design and operation. Tests should include collection of ash samples from various points in the furnace and convection section. The samples should be analyzed for calcium content and mixed with water to determine the ash settling and cementitious properties. These latter two properties are especially important in the operation of wet ash removal systems while the degree of ash entrainment determines the necessary ash removal system design capacity.

Data from the TVA Shawnee tests[4] indicated that practically all of the limestone solids were entrained by the combustion gases, but the injected limestone particles were fairly small in size. Also, TVA reported plugging of fly ash sluicing systems due to the cementitious nature of the collected ash. Ash entrainment and physical properties as functions of both injected limestone particle size and combustion gas flow rate should be measured.

Another useful test objective is to determine the influence of LIMB on erosion in the convection passes but this would require relatively long term testing. Limestone injection will significantly increase the total flue gas solids loading. Also, limestone inerts include those compounds thought to contribute most to erosion - SiO_2 and Fe_2O_3. Testing would involve measurement of the change in weight of metal probe samples installed in the convection section of a pilot unit.

Other research needs include studies of limestone grinding characteristics. As indicated in Section 7 of this report, simultaneous grinding of coal and limestone may be a desirable alternative at facilities which have excess pulverizer capacity. However, the effects of simultaneous grinding are relatively unknown. Tests of simultaneous grinding for ranges of coal and limestone types, inlet limestone rock sizes, and pulverizer designs should be considered. The test objectives would be to observe the adequacy of mixing of coal and limestone; the effects of limestone addition rate on pulverizer capacity, power requirements, and reliability; and the effects of simultaneous grinding on resulting coal and limestone particle size distributions. A related research need which may prove valuable in design of limestone feed systems is to develop a data base of Hardgrove Grindability Index, hardness, and particle specific gravity values for a range of commercially available limestone types.

Engineering Analysis Needs

Several areas have been identified in which additional engineering analyses would be useful. These include additional analyses of the boiler system, analyses of downstream emission control systems, and overview type analyses of the system as a whole. All of this information should be combined with the material presented in this report into a final report covering the entire LIMB-based system. These proposed additional analyses are discussed below.

Important information for assessing the usefulness of LIMB as a retrofit technology is the design profile of the existing boiler population. Limited material on this subject is presented in this report. However, more specific data are available. Specifically, DOE maintains a computer data base containing information on every utility boiler in the country. Some of the useful information includes unit capacity, startup year, furnace type, boiler manufacturer, coal consumption, and coal composition. Conceivably, this information could be cross referenced with information from available FGD system data bases or survey reports (such as the EPA sponsored "Utility FGD Summary Reports") to provide a fairly complete picture of the existing boiler population and the potential for LIMB retrofit applications. Unfortunately such an undertaking was beyond the scope of this study.

Further research should also be conducted into previous limestone injection tests in large pilot- and full-scale systems. The objective would be to summarize data on SO_2 removal and system operating problems and relate this information back to boiler design. Although SO_2 removal data may be of limited applicability to current research, as previous research efforts have been conducted at oxidizing furnace conditions, results from these efforts may help better characterize boiler system impacts and their relationship to boiler design and operating conditions.

An additional worthwhile effort would be to research the furnace dimensions or plan areas (cross sectional areas) of the existing boiler population. This information would provide insight about potential unit derating resulting from retrofit of LIMB technology. Such derating may be brought about by the large flame volumes required by the low NO_x burner techniques instrumental to the application of LIMB technology, such as the distributed mixing burner concept.

For a complete systems analysis, engineering evaluations are also needed of the impact of LIMB on downstream particulate control systems. Flue gas solids loadings are greatly increased and the particle characteristics are altered by LIMB. Analyses should be conducted to evaluate which particulate control systems are best suited for LIMB applications and to choose the best methods for upgrading existing control systems in LIMB retrofit applications. A related need is to evaluate alternatives for recovering unused sorbent from the fly ash and recycling it to the boiler.

Finally, overall system material and energy balances and cost analyses could be conducted for a number of cases involving different coal types, system sizes, limestone injection rates, injection system designs, and particulate control system designs. These analyses would highlight areas of technological and cost benefits associated with LIMB technology and provide justification for continued research efforts related to the development of LIMB.

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SECTION 3

SUMMARY OF RESULTS

This report presents background information concerning coal and limestone chemical/physical properties, limestone handling and preparation, and boiler design and operation. This information was used together with a knowledge of the LIMB process to assess the likely system impacts resulting from the application of LIMB to pulverized coal boilers. This section highlights the major findings developed in this study and discussed later in this report. These findings are outlined below.

RAW MATERIAL AND ENERGY REQUIREMENTS/IMPACTS

The application of LIMB technology to pulverized coal boilers requires consumption of significant quantities of limestone. Below are presented findings related to analyses of limestone availability and properties, limestone requirements of LIMB, and the overall system impacts resulting from these requirements.

- Large limestone deposits are available throughout the U. S. However, for coal fired boilers in some locations high-calcium limestone may have to be transported over relatively long distances (a few hundred miles) because of a lack of local deposits. These locations include some areas along the East coast; in Minnesota, Wisconsin, and North Dakota; and in various parts of the West.

- As with coals, limestones have a wide range of chemical and physical properties, such as chemical composition, hardness, grindability, specific gravity, and bulk density. These properties affect the limestone handling requirements; design of handling, preparation, and injection equipment; processing energy requirements; and boiler thermal losses.

- Raw limestone is available as crushed rock from 0.6 to 12 cm (0.25 to 5 inches) size, or prepulverized as fine as 96 percent, through 325 mesh (44μ) size. However, prepulverized limestone costs two to six times that of crushed limestone. For rock sizes greater than 3.8 cm (1.5 inches), a crusher will need to be included in the limestone handing system. A complete site-specific economic analysis of the raw material choices would determine which alternative is most cost effective.

- Several factors affect the required limestone injection rate including the coal firing rate, coal sulfur content, Ca/S molar ratio, and limestone calcium content. Typical limestone injection requirements may range from about 10 to 30 percent of the coal firing rate.

- These limestone feed rates would generally result in the need for railcar or barge unloading facilities for receiving limestone shipments; truck load shipments would only be practical at facilities smaller than about 100 MW_e.

- Limestone injection significantly increases the boiler system ash or solids loading. Example calculations showed increases of over 50 percent for a low sulfur coal and over 100 percent for a high sulfur coal. Important factors include the Ca/S molar ratio and the coal sulfur/ash ratio.

- Calculated electrical power requirements for handling, pulverizing, and injecting limestone ranged from 32 to 76 kWh/Mg (30 to 70 kWh/ton) of crushed limestone received, depending on the preparation and injection technique and desired particle size. Variations in limestone physical properties would affect these power requirements even further. Example calculations, using a nominal power requirement of 55 kWh/Mg (50 kWh/ton) of limestone, showed a loss in net boiler system power efficiency of about 0.3 percent for a low sulfur coal and about 0.7 percent for a high sulfur coal.

- Limestone injection also results in a net boiler thermal efficiency loss. Example calculations showed losses of about 0.6 percent for a low sulfur coal and 1.0 percent for a high sulfur coal. Important factors include the quantity of limestone injected and the extent of the calcination and sulfation reactions. These results are in addition to any effects associated with changes in boiler excess air requirements or in slagging and fouling.

- Thus, limestone injection may cause a change in the boiler coal firing rate. The rate may increase or decrease depending on how the compromise is made between minimizing capital investment associated with LIMB application and maintaining the boiler net MW_e power output.

ALTERNATIVE LIMESTONE INJECTION SCHEMES

Several alternative limestone injection schemes could potentially be used in LIMB applications. Any of these alternatives may prove best for a particular application. Below, these alternatives are identified and their relative merits compared.

- Four basic limestone preparation and injection schemes are available for use in LIMB applications. These include:

Alternative A - crushed limestone and raw coal mixed, pulverized together, and injected through the burners;

Alternative B - ground limestone and raw coal mixed, passed through the coal pulverizer together, and injected through the burners;

Alternative C - ground limestone pneumatically mixed with pulverized coal and primary air and injected through the burners; and

Alternative D - separate furnace injection of ground limestone through combustion air ports or other ports installed on the furnace walls.

- Several variations on these four basic schemes are possible. For example, combinations of the above alternatives could be used such as simultaneous injection of limestone through the burners and through other ports on the furnace walls. Also, alternatives B, C, and D which involve separate grinding of limestone and coal, could include limestone grinding at an on-site grinding mill (either close to the boiler or at a remote location) or purchase of prepulverized limestone.

- Selection of the best alternative for a particular application depends on several factors. These include the design of the existing coal feed system, relative limestone and coal physical properties, desired flexibility to alter the limestone particle size or the time-temperature environment seen by the limestone particles, and the compromise made between minimizing capital investment and maintaining the boiler net power output.

- Alternative A would be the best selection if the coal pulverizers have sufficient excess capacity for limestone and coal; the limestone grindability is near or higher than that of the coal; the limestone moisture content is near or less than that of coal; a pressurized primary air supply system is used; the coal pulverizer and firing system can handle the expected extra wear from limestone abrasion; SO_2 removal considerations permit burner injection; and SO_2 removal considerations permit the resulting limestone particle sizes.

- Alternative B allows the advantage over A for controlling the limestone particle size, but at higher capital investment for a separate grinding mill.

- Alternative C has the advantage over A and B of not affecting the coal preparation system.

- Alternative D should be used if injection through the burners is not optimum for SO_2 control.

- Purchase of prepulverized limestone would reduce capital investment and space requirements for limestone handling and processing equipment. However, prepulverized limestone costs considerably more than raw limestone, so an economic analysis would be needed to determine the practicality of this option.

DESIGN PROFILE OF BOILER POPULATION

The general applicability of LIMB as a retrofit technology is dependent on the design profile of the existing boiler population. Major findings related to this design profile are as follows.

- A large majority of the pulverized coal boiler capacity in the U.S. is represented by utility boilers.

- As of 1978, about 75 percent of the existing coal fired utility boiler capacity was designed for bituminous coal.

- Of the capacity designed for lower rank coals, about 90 percent was installed in the 1970s.

- Average unit capacities designed prior to 1965 were smaller than average capacities designed after that time.

- With the exception of the earliest designs, boilers designed for low rank coals are roughly similar in capacity to those designed for bituminous coals.

- Almost all pulverized coal boilers use either wall fired or tangentially fired furnaces.

- Most wall fired boiler capacity uses opposed firing.

- All units designed since the early 1970s are dry bottom units. Most of the units designed before that time are also dry bottom units.

- In the 1960s, units were designed with higher heat release rates than is current practice.

- Boiler manufacturers have improved their capabilities to build large furnaces. Many units designed in the 1960s and earlier employed furnaces with center division walls.

However, existing NO_x control technologies for coal-fired boilers reduce emissions by only about 30 to 40 percent. Existing SO_x control technologies can achieve control levels of about 90 percent, but improvements in cost effectiveness are desirable. In addition, space requirements may prevent retrofit applications on many existing boilers. To address these problems, retrofittable lower-cost SO_x control technology and more effective NO_x control technology are needed for both new and existing sources. The LIMB program will address these needs through development of low-cost, combustion related techniques for controlling SO_x and NO_x emissions from pulverized coal boilers.

The program goal is to develop the technology to obtain substantial reductions in SO_x and NO_x emissions for a capital investment cost of 30-40 $/kilowatt - about 1/5 of the cost of conventional flue gas desulfurization (FGD) systems. For cases involving retrofit of the technology on existing pulverized coal boilers, the goal is to achieve about 50 percent SO_x control and NO_x emission levels of 130-170 ng/J (0.3-0.4 lb/million Btu) thermal input. For new boiler applications the goal is to achieve even higher SO_x removals while achieving NO_x emission levels of 86-130 ng/J (0.2-0.3 lb/million Btu).

REPORT ORGANIZATION

For evaluative purposes the boiler system, and the equipment necessary for the application of LIMB have been divided into three major subsystems. These are the (1) the limestone feed system, (2) boiler (steam generation) system, and (3) downstream emission control systems. Technical analyses presented in this report focused primarily on retrofit applications for the first two subsystems. Future analyses will include evaluation of the third subsystem.

This report is organized as follows:

Section 2 - Conclusions and Recommendations
presents a summary of conclusions based on technical analyses of the limestone feed and boiler systems and makes recommendations about information needs to better define system impacts and to further develop LIMB technology;

Section 3 - Summary of Results
presents a more extensive list of results developed in this study;

Section 4 - Development of LIMB Technology
describes the SO_x and NO_x control aspects of the LIMB technology and how it has evolved;

Section 5 - Coal and Limestone Resources
discusses physical and chemical properties of coal and limestone resources to serve as background for technical evaluations presented in later sections;

BOILER INJECTION IMPACTS

The most significant finding resulting from systems analysis of the boiler system is that existing boilers firing low rank coals appear well suited for LIMB application, but existing boilers firing bituminous coals may not be well suited. Low rank coals generally have lower sulfur contents thus requiring lower limestone injection rates. This lowers limestone handling and processing requirements, reduces total system energy losses, and reduces boiler solids loading impacts. Also, low rank coal ash chemistry is such that limestone injection is not likely to aggravate slagging and fouling. Additionally, most boilers firing low rank coals were designed in the 1970s with more conservative design criteria concerning furnace sizing and convection pass spacing than earlier bituminous coal units. Finally, units firing low rank coals do not usually employ fly ash wet sluicing systems which may plug with high-calcium fly ash.

Some specific boiler evaluation findings are outlined below.

Furnace Operation Impacts

- The increased combustion zone requirements of the low NO_x burners associated with LIMB may require derating of some existing units - especially those designed with high heat release rates such as 1960's bituminous coal units.

- Very high rates of limestone injection may potentially result in flame stability problems if the limestone is injected through the burners or in excess air control problems if pneumatic injection is used.

- Large reductions in peak flame temperatures with the low NO_x burners may help reduce slag formation.

- However, injected limestone particles may chemically interact with ash particles in the furnace, altering the ash melting characteristics and slagging potential. Important factors are the extent of interaction, which is unknown, and the type of coal. Slagging may increase with bituminous coals but should not with lower rank coals.

- Potential methods of controlling increased slagging associated with LIMB include increasing sootblowing and boiler excess air (if allowed with the low NO_x burners) and reducing boiler load and pulverized coal size.

- Furnace ash removal systems for dry bottom units will probably not be adversely affected by LIMB since almost all of the limestone solids appear to be entrained by the combustion gases. With wet bottom units, however, the impacts could be severe. Lower flame temperatures of the low NO_x burners would probably reduce the slag temperature and therefore its fluidity, possibly plugging the furnace bottom. For a constant slag temperature, chemical interactions between the limestone solids and coal ash could increase the slag fluidity for bituminous coal units and decrease it for units firing low rank coals.

Convection Section Operation Impacts

- Limestone injection will probably not adversely affect fouling in units firing low rank coals. In fact, available information indicates that limestone injection reduces deposit strength.

- Limestone injection may increase fouling or plugging of convection passes in units firing bituminous coals. This problem could result due to greatly increased solids loadings, tight tube spacings, and lowered ash fusion temperatures.

- Potential methods of controlling increased convection pass deposits associated with LIMB are similar to the methods used to control slagging. These include increasing sootbloowing, flue gas tempering, and boiler excess air (if allowed with the low NO_x burners). Other methods include reducing boiler load and pulverized coal size.

- Limestone injection will likely increase erosion to some extent due to the increase in flue gas solids loading.

- It will reduce cold end corrosion by removing SO_3 from the flue gas. Some experiences have indicated that high temperature corrosion may also be reduced.

- The increased flue gas solids loading could potentially overwhelm the capacity of existing economizer and air heater ash removal systems. Also, the high calcium and sulfate ash will likely exhibit cementitious properties, causing plugging problems in units employing ash sluicing systems.

Effect of Boiler Design on LIMB Performance

- Two boiler design variables which will likely affect the SO_x/NO_x control performance of LIMB are the time-temperature and reducing-oxidizing histories of the combustion gases.

- NO_x control is enhanced by those types of boilers or burners which maximize fuel combustion under reducing conditions and minimize gas temperatures which occur under oxidizing conditions.

- The precise effects of these variables on SO_x control are not clear at the present time and may vary depending on the mechanism by which sulfur is captured. However, the time-temperature profile is probably least suited for LIMB in units with high furnace heat release rates such as those units designed in the 1960s for low slagging and fouling bituminous coals. These units may require derating to achieve good LIMB performance.

- The ongoing EPA research and development effort should elucidate the final boiler design effects based on fundamental, pilot, and prototype studies.

SECTION 4

DEVELOPMENT OF LIMB TECHNOLOGY

LIMB is a technology designed for simultaneous SO_x and NO_x control on pulverized coal boilers. It is an attempt to combine a previously tested technology, dry sorbent injection into the furnace for SO_x control, with low NO_x combustion techniques currently under development by EPA. This section briefly describes the combined technology and its evolution.

TECHNOLOGY DESCRIPTION

The term "LIMB" is short for Limestone Injection/Multistaged Burners. This title could easily include the word "sorbent" instead of "limestone" since other sorbents will also be evaluated in the program. However, limestone is the sorbent currently receiving the most emphasis because of its abundant supply and low cost. "Multistaged burners" is a term describing the low NO_x combustion techniques under development by EPA. These techniques delay the mixing of fuel and combustion air at the burner thereby creating an environment less conducive to NO_x formation.

Thus, the LIMB technology consists of two distinct features: (1) low NO_x combustion techniques and (2) dry sorbent injection into the furnace for simultaneous SO_x control. Each of these features is briefly described below.

EPA has been developing low NO_x combustion modification techniques for some time under the ongoing low NO_x program. The results of the low NO_x program will help guide development of the LIMB technology. While the goal of the low NO_x program is to maximize NO_x control alone, the LIMB program will attempt to maximize both NO_x and SO_x control. Hence, the LIMB program will make use of those low NO_x combustion modification techniques which appear most promising for simultaneous SO_x control and attempt to optimize their design and operation for maximum SO_x and NO_x control.

The primary approach to more effective NO_x control is the development of advanced burner designs applicable to conventional boilers. The EPA effort addresses new and retrofit applications for both wall fired and tangentially fired pulverized coal boilers.

The approach for wall fired boilers, called the distributed mixing burner (DMB), is shown conceptually in Figure 4-1. Figure 4-1 represents a cross section of half of the DMB burner, from the center line of the burner up. The technique consists of staged burner design. Coal and

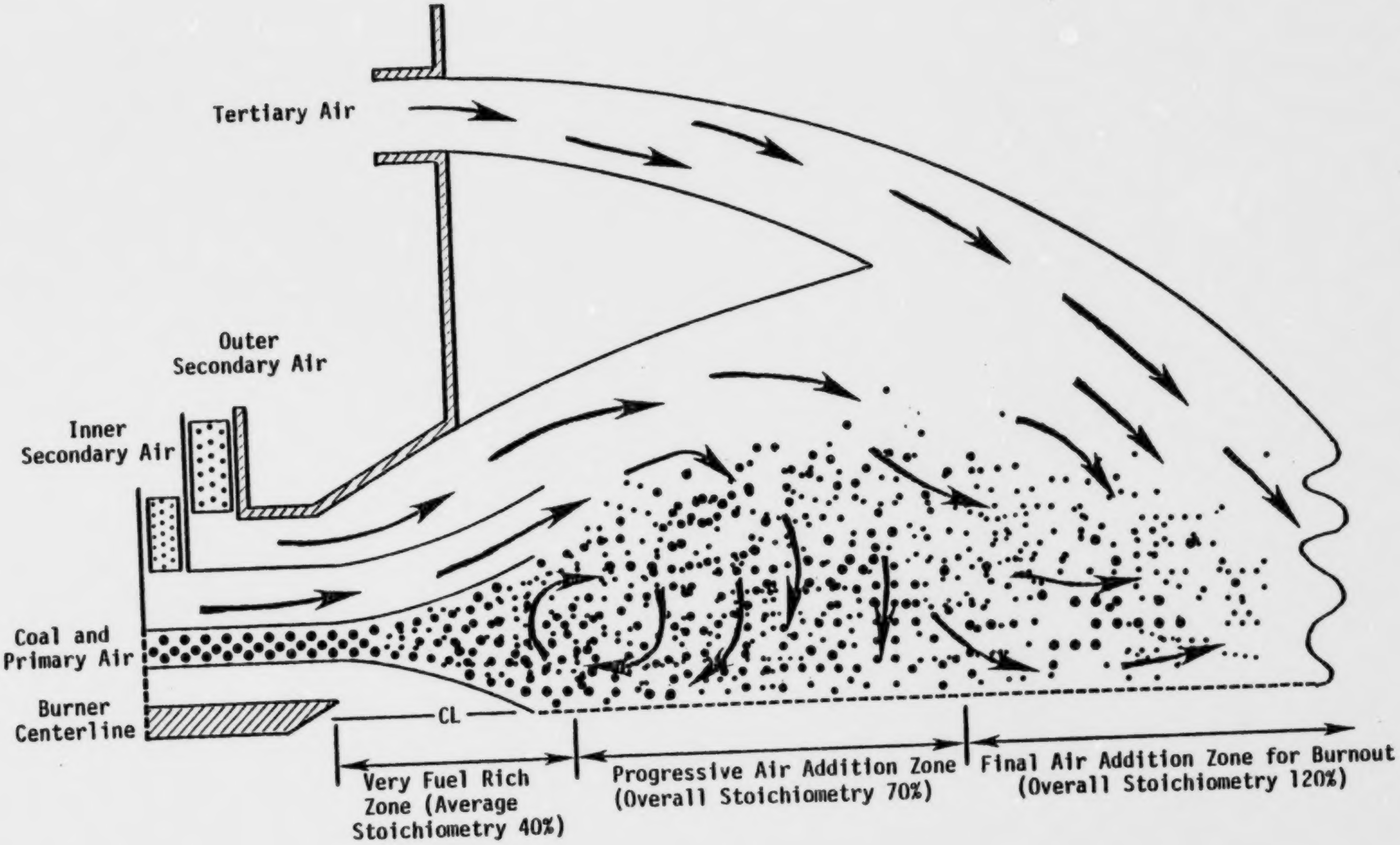
Tertiary Air
Outer Secondary Air
Inner Secondary Air
Coal and Primary Air
Burner Centerline
CL
Very Fuel Rich Zone (Average Stoichiometry 40%)
Progressive Air Addition Zone (Overall Stoichiometry 70%)
Final Air Addition Zone for Burnout (Overall Stoichiometry 120%)

Figure 4-1. Multistage combustion in the distributed mixing burner (top half of burner only depicted).[a]

[a] Figure redrawn from figure presented in reference 1.

primary combustion air are injected through a central fuel injector and the coal begins to burn in a very fuel-rich zone. Secondary air is admitted through two concentric throats and gradually mixes with the primary reactants. The final mixture in the burner zone is still fuel-rich, having about 70 percent of the air required for complete combustion. The fuel-rich conditions minimize formation of NO_x from nitrogen chemically bound in the coal, by promoting maximum conversion to molecular nitrogen. The balance of the air necessary for complete combustion is admitted through tertiary ports spaced around the burner periphery. The delayed combustion also reduces peak flame temperatures, which minimizes NO_x formation from thermal fixation of nitrogen present in the combustion air. To provide the necessary energy input the burners are placed in rows on one or two opposing walls of the furnace.

Tangentially fired boilers require a different approach to achieve the same results. In this case, the coal and primary combustion air are introduced in a jet which penetrates most of the width of the furnace. The jet is directed on the tangent of an imaginary circle in the center of the furnace. Secondary air is introduced in the same vertical plane at elevations both above and below the fuel jet. The balance of the combustion air is introduced in the same horizontal plane as the fuel jets but directed at an angle closer to the furnace wall. By mounting one such assembly at each corner of the furnace, a fuel-rich fireball is formed in the center of the furnace. This design generates the same type of delayed mixing as the DMB described above and produces similar NO_x reductions. In practical boilers multiple burner elevations are used to provide the necessary energy input. A plan view of the fuel rich fireball is shown schematically in Figure 4-2.

LIMB serves to reduce SO_x emissions by the injection of a dry sorbent directly into the furnace. Sulfur compounds formed during combustion react with and are retained on the solid sorbent particles. These particles are collected by a downstream particulate control system such as an electrostatic precipitator or fabric filter. Several methods for preparing the sorbent and injecting it into the furnace are under consideration. One such method is shown in Figure 4-3. As shown, the sorbent is coarsely ground and fed with the coal into the pulverizer where it is finely ground and intimately mixed with the coal. The coal and sorbent mixture is injected into the furnace with the primary air. Other methods involve injection of sorbent independently of the coal through secondary or tertiary air ports, or at other points in the reaction zone. Technical evaluations of various limestone handling and preparation system designs are presented in Section 7.

TECHNOLOGY EVOLUTION

The two major components of LIMB, low NO_x combustion techniques and dry sorbent injection into the furnace, are not recently developed technologies. Work has previously been conducted in each of these areas.

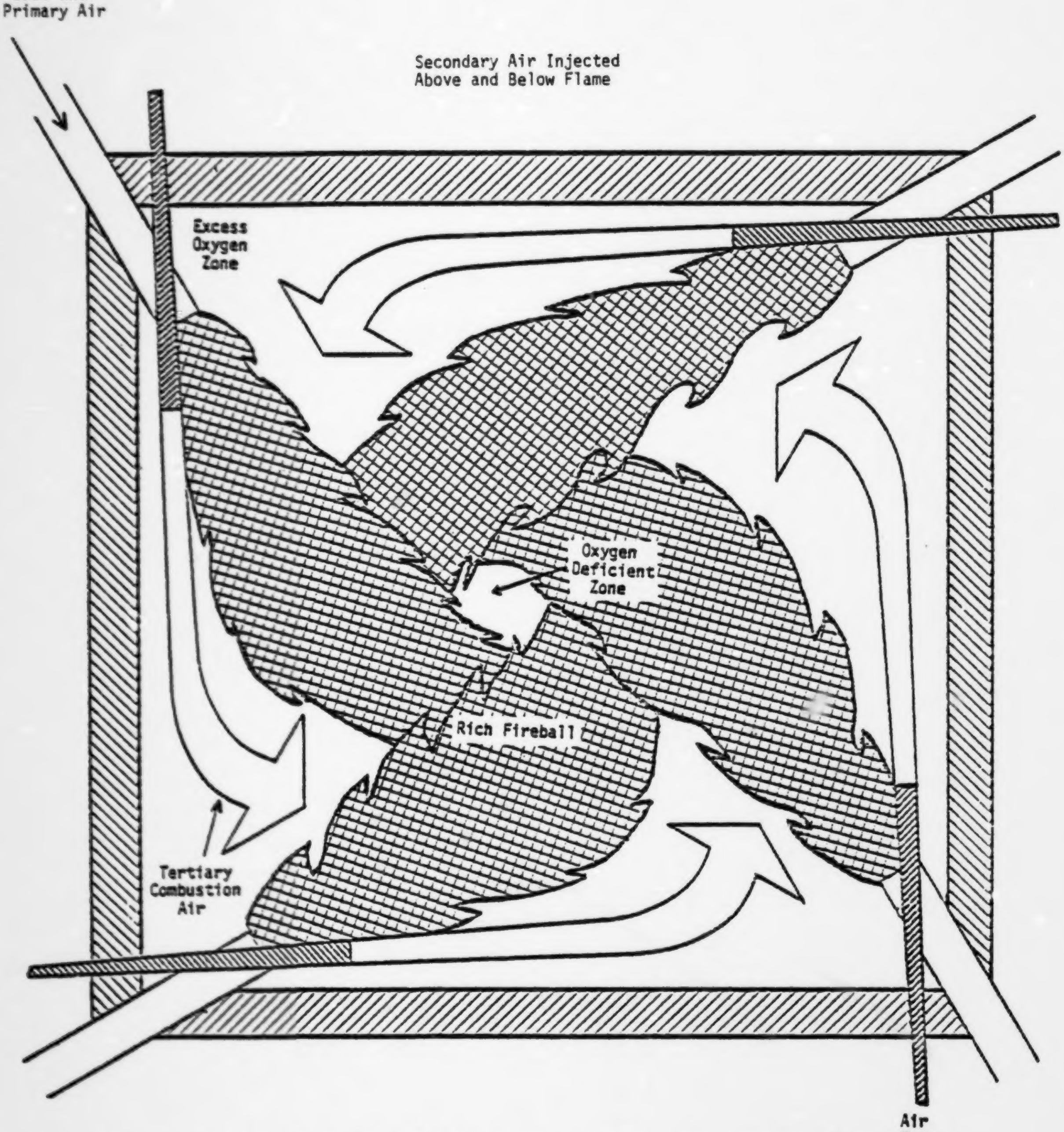
Cool and
Primary Air
Secondary Air Injected
Above and Below Flame
Excess
Oxygen
Zone
Oxygen
Deficient
Zone
Rich Fireball
Tertiary
Combustion
Air
Air
Vane

Figure 4-2. Fuel rich fireball burner design for tangentially fired boilers (plan view).[a]

[a] Figure redrawn from figure presented in reference 1.

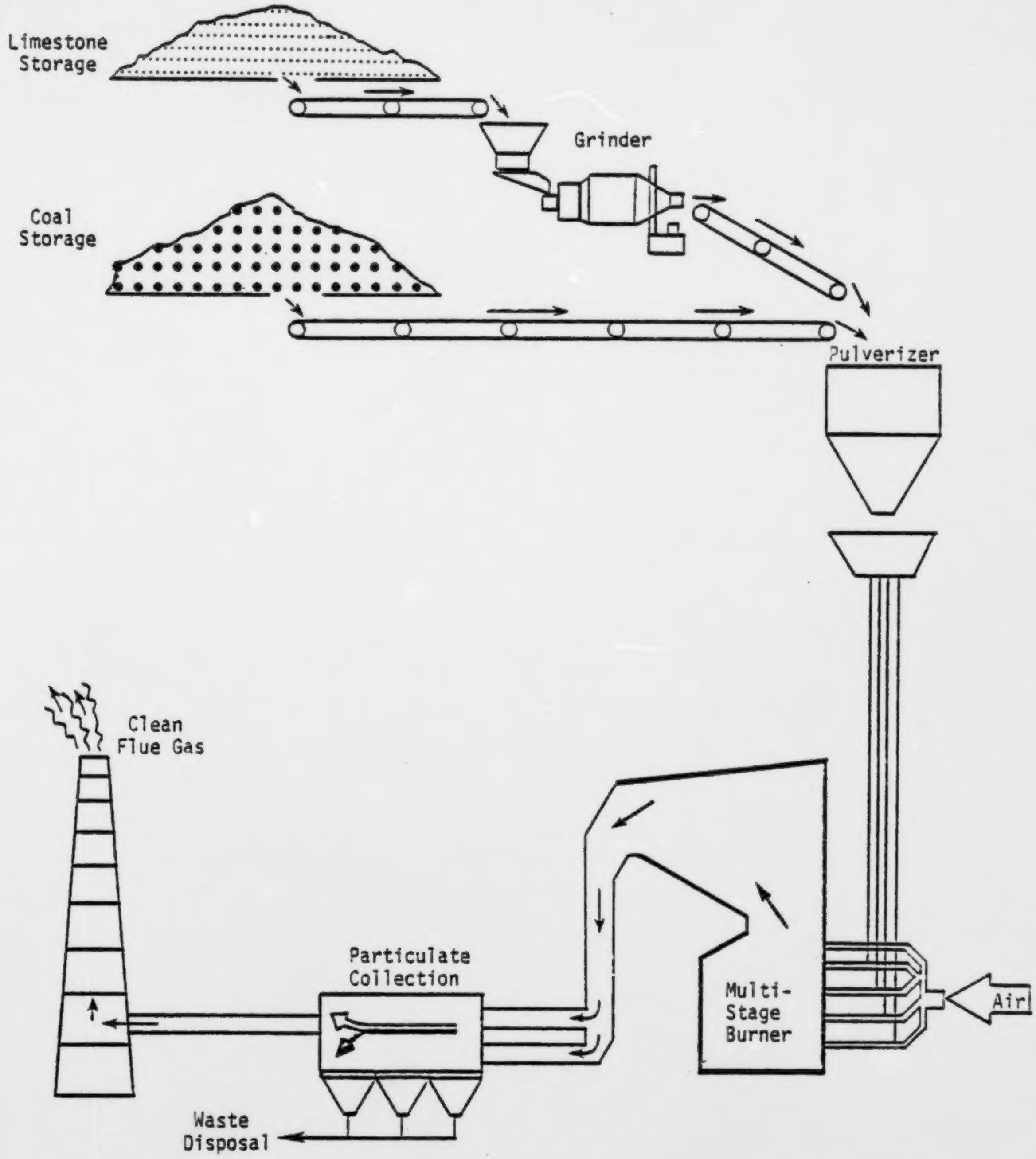
Limestone Storage
Grinder
Coal Storage
Pulverizer
Clean Flue Gas
Particulate Collection
Multi-Stage Burner
Air
Waste Disposal

Figure 4-3. Example schematic flow diagram of the limestone injection multistage burner process.[a]

[a] Figure redrawn from figure presented in reference 1.

First generation low NO_x burners developed by various boiler manufacturers are already being installed on utility-scale coal fired boilers. Further, EPA's low NO_x program has produced very encouraging pilot-scale test results with more advanced burner designs such as the distributed mixing burner for wall fired units and the fuel rich fireball for tangentially fired units. Field evaluations of these two burner designs are planned by EPA on commercial size industrial and utility boilers. Evaluations of the wall fired burner on an industrial unit and of the tangential burner on a utility unit are currently in progress.

Considerable work has also been conducted on controlling SO_x emissions with dry sorbent injection into the furnace. Most of this work used conventional combustion techniques and met with only limited success. However, recent pilot studies and theoretical considerations have indicated that low NO_x combustion techniques may considerably improve the combustion environment for SO_x control by dry sorbent injection. This work is discussed further below.

The use of dry limestone injection into the furnace for controlling SO_x emissions was explored extensively in the late 1960s and early 1970s. SO_x removals for a variety of boilers of different design ranged from about 18 to 40 percent at calcium-to-sulfur molar ratios of up to two-to-one. However, SO_2 removal appeared to be dependent on boiler design as well as calcium-to-sulfur ratio. Better results were obtained on inherently delayed mixing boiler types such as arch or tangentially fired systems. The low level of SO_x removal was attributed to two factors: (1) deadburning of the limestone and/or instability of calcium-sulfur reaction products at high temperature; and (2) inadequate mixing of the sorbent with the combustion gases. Since the goal of this effort was to achieve high removal efficiencies (80 to 90 percent) competitive with wet control methods, further study of the technique was abandoned in the early 1970s.

Recently, three factors have led to renewed consideration of the control technology. First, altered combustion conditions associated with low NO_x combustion systems lead to lower peak flame temperatures and results in the possibility of forming more stable calcium-sulfur species under reducing conditions. Second, the desire for low cost retrofit SO_x control technology might promote acceptance of removal levels lower than those achievable with wet FGD systems. Finally, limited pilot-scale test results indicate that low NO_x combustion techniques may improve the effectiveness of SO_x control by dry sorbent injection.

Because low NO_x burner technology involves the delayed mixing of fuel and air in the active combustion zone, conditions are created which may be favorable to improved sulfur capture and/or retention. These conditions include: (1) lower peak and average temperatures in the burner zone; (2) a fuel-rich stoichiometry which may favor initial formation of more stable calcium-sulfur compounds; (3) flame calcining of the limestone with an apparently higher resulting activity; (4) improved contacting of the active sorbent with high concentrations of sulfur species; and (5) longer residence times in the optimum reaction zone of the furnace. Although none of these hypotheses are proven, they provided a technical rationale for re-examining the control technology.

Some recent tests have generated optimism about the potential for SO_x emission reductions with LIMB technology. A few of these tests are mentioned below.

The most advanced effort to date has been carried out by Dr. Klaus Hein of Rhienisch-Westfailsches Electrizitatswerk (RWE) in the Federal Republic of Germany. His work involves firing of brown coal in tangentially fired pulverized coal boilers. Brown coal is a low rank coal similar to a low quality lignite. These boilers operate at relatively low combustion zone temperatures due to the high moisture content of brown coal (up to 60 percent) and the flue gas recirculation used for drying. These conditions are thought to be favorable for sulfur capture by the sorbent and for the production of relatively low NO_x emissions. The system was tested on a 60 MW boiler where SO_2 reductions of over 60 percent were achieved on a low sulfur coal. Tests on a 300 MW boiler are planned in 1982-83. Though the information generated at RWE is not directly applicable to black coal fired units in the United States because of large differences in both coal and boiler characteristics, it does provide valuable insights.

Other tests include those run by Steinmuller, a major German boiler manufacturer. Steinmuller ran bench-scale experiments using natural gas doped with sulfur compounds. They also ran 2 MW_t pilot-scale tests with sulfur-doped natural gas and pulverized coal. The pilot-scale burner is a staged burner, the design of which is based on earlier EPA work on the distributed mixing burner. Using a proprietary calcium-based sorbent, Steinmuller has achieved up to 70 percent SO_x control at a calcium-to-sulfur stoichiometry of two-to-one.

In 1979, EPA sponsored a limited series of experiments on sorbent injection at a government-owned 4 MW_t pilot facility equipped with an experimental distributed mixing burner. The burner was operated staged and unstaged with two bituminous coals (one high-sulfur and one low-sulfur) and a variety of sodium- and calcium-based sorbents. At optimum conditions up to 70 percent sulfur removal was measured with limestone sorbent at a calcium-to-sulfur stoichiometry of two-to-one. These initial tests, although not verified by detailed material balance determinations, resulted in hypotheses about the controlling phenomena of the process and led to the definition of the LIMB program.

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SECTION 5

COAL AND LIMESTONE RESOURCES

This section presents background information concerning coal and limestone resources with emphasis on discussion of their chemical and physical properties. The information is divided among five major subsections. The first two discuss the types of coal available and its properties. The third focuses on coal ash properties and their influence on boiler slagging and fouling. The last two discuss the types of limestone available and its properties. These properties affect the design and operation of the boiler and raw material handling subsystems. These effects and their influence on LIMB applications are discussed in later sections of this report.

COAL TYPES

Coals are classified to determine end use and to provide process design data. Coal classification is usually by rank or quality; that is according to its natural degree of metamorphism from vegetal matter into high rank coal. Volatile matter, fixed carbon, moisture, and oxygen contents are collectively indicative of rank, but no single characteristic completely defines it. The most common basis for coal classification, established by the American Society for Testing and Materials (ASTM), uses the fixed carbon content and higher heating value calculated on a moist, mineral matter free basis to define coal rank. Under the ASTM method the lowest rank class of coal is called lignite. Succeedingly higher rank classes are called subbituminous coal, bituminous coal, and anthracite.

Figure 5-1 illustrates the change in coal quality with rank. As shown, increases in coal rank are generally associated with increases in fixed carbon content and heating value and with decreases in moisture content. Also, the higher rank bituminous and anthracite coals contain smaller proportions of volatile matter than the lower rank coals. Although not shown in the figure, another characteristic of increasing coal rank is decreasing oxygen content.

Figure 5-2 shows the principal locations of U. S. coal deposits by type. Generally, coals tend to decrease in rank as one proceeds from the East to the West. Anthracite is found primarily in eastern Pennsylvania. Deposits of this coal type are relatively scarce and it is no longer widely used as a fuel for power plants. Also found in the East are large bituminous coal deposits extending along the Appalachian Mountains from western Pennsylvania to Alabama. While these deposits vary in quality, a large proportion consists of high rank low-to-medium volatile

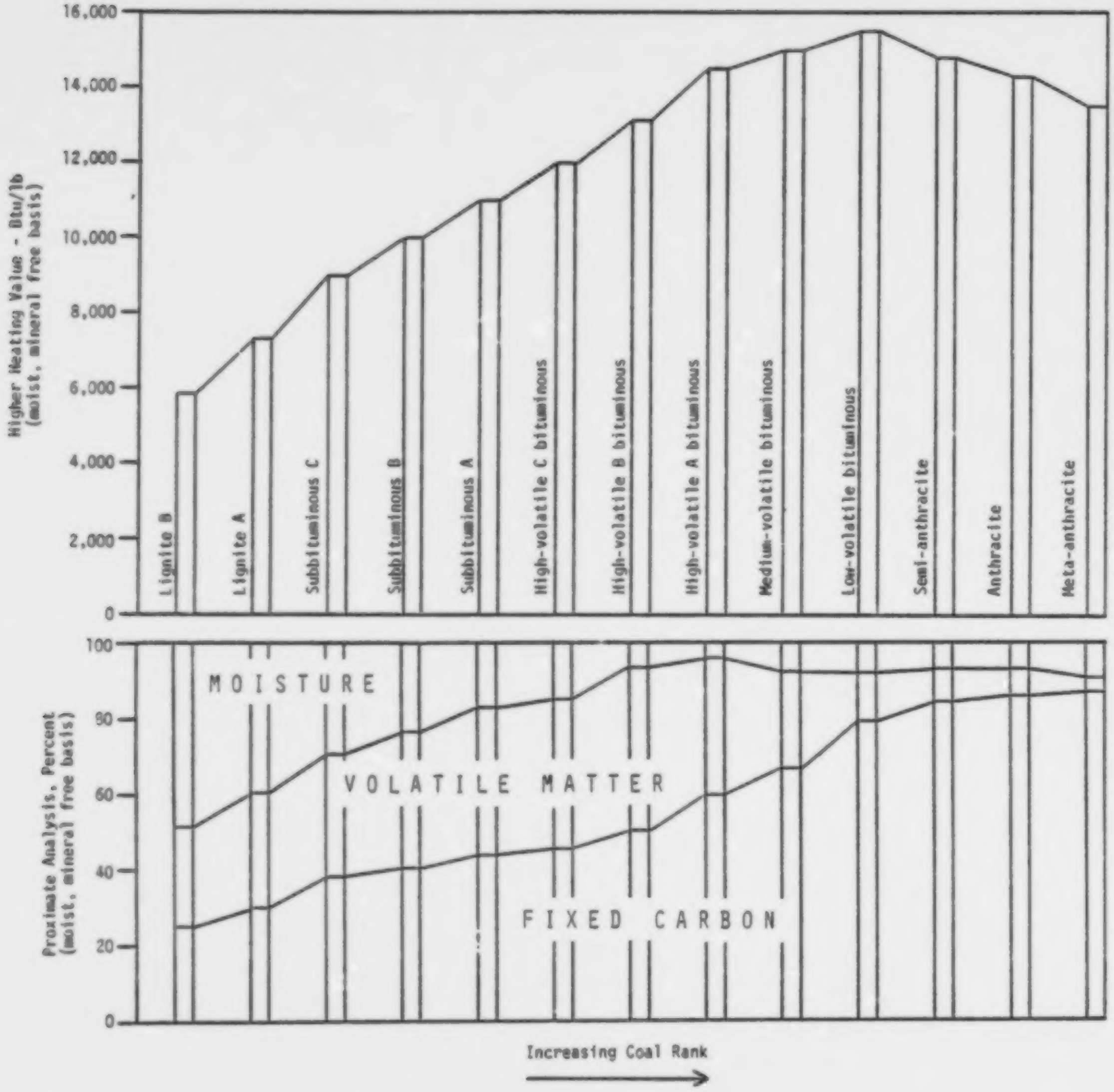
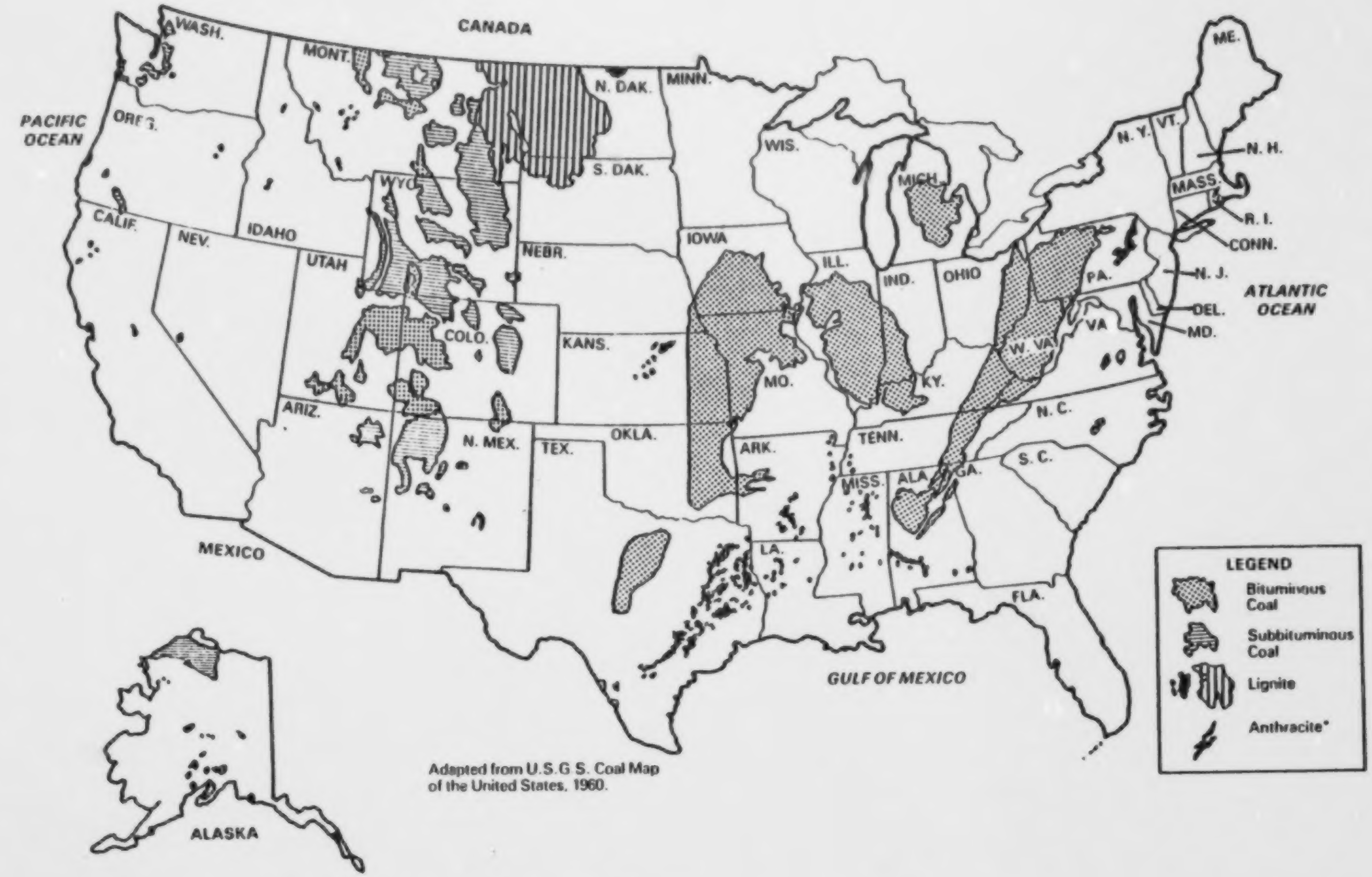


Figure 5-1. Effect of coal rank on higher heating value and proximate analysis.[a,b]

[a] Redrawn based on figure presented in reference 1.

[b] Multiply Btu/lb by 2.325 to obtain J/g.


CANADA
PACIFIC OCEAN
ATLANTIC OCEAN
GULF OF MEXICO
MEXICO
ALASKA
WASH.
OREG.
CALIF.
NEV.
IDAHO
MONT.
WYO.
UTAH
ARIZ.
COLO.
N. MEX.
N. DAK.
S. DAK.
NEBR.
KANS.
OKLA.
TEX.
MINN.
IOWA
MO.
ARK.
LA.
WIS.
ILL.
MICH.
IND.
OHIO
KY.
TENN.
MISS.
ALA.
GA.
FLA.
S. C.
N. C.
VA
W. VA.
PA.
N. Y.
VT.
N. H.
ME.
MASS.
R. I.
CONN.
N. J.
DEL.
MD.
LEGEND
Bituminous Coal
Subbituminous Coal
Lignite
Anthracite*

Adapted from U.S.G.S. Coal Map of the United States, 1960.

*Principal deposits in Pennsylvania; small deposits in Arkansas, Colorado, New Mexico, and Virginia. Anthracite - meta-anthracite deposits in Massachusetts and Rhode Island

Figure 5-2. Coal fields of the United States.[a]
(Coal rank not distinguished in Alaska)

[a] Reprinted from reference 2.

bituminous coal. Large bituminous coal deposits are also found in the Midwest, primarily in Illinois, Indiana, and western Kentucky and extending into Michigan, Iowa, Missouri, Nebraska, Kansas, Oklahoma, and Texas. These deposits tend to be lower rank, higher volatile bituminous coals than the Eastern coals.

The major U. S. subbituminous coal deposits are located in the West in Montana and Wyoming and extending into Colorado and New Mexico. The largest lignite deposits in the world are found in the Northern Plains states of North Dakota, South Dakota, and Montana. Large lignite deposits are also found in states along the Gulf Coast, primarily in Texas and extending into Louisiana, Arkansas, Tennessee, Mississippi, and Alabama.

COAL PROPERTIES

Design and operation of steam generators and coal handling equipment are significantly influenced by coal properties. Ranges of representative properties for five major coal types are presented in Table 5-1. Composition and grindability are the two coal properties of most significance for application of limestone injection. However, other properties such as specific gravity, hardness, and heating value are also of interest.

Composition

Coal is composed of a number of elements and compounds, knowledge of which is necessary for proper boiler design. Also, coal properties which affect coal handling system design vary widely with coal composition. Boiler designers are especially interested in the results of the proximate analysis and in the coal sulfur content. The proximate analysis includes measurement of moisture, volatile matter, fixed carbon, and ash. Ranges of coal moisture, sulfur, and ash contents by coal type are reported in Table 5-1.

As previously discussed, moisture content is related to coal rank and ranges from less than two percent for some high rank Eastern bituminous coals to over 40 percent for some low rank lignite coals. Moisture content directly affects the coal heating value which decreases as the moisture increases. It also affects other coal properties, such as the grindability as discussed later.

The sulfur content of coals also varies widely. This content directly influences flue gas SO_2 emissions and thus the quantities of limestone required by LIMB. Eastern bituminous coals generally have low to medium sulfur content; however, some deposits have up to four percent sulfur. Midwestern bituminous coals characteristically have high sulfur contents of three to four percent and can range up to about seven percent. In comparison, most of the western subbituminous and lignitic coals have less than one percent sulfur.

TABLE 5-1. COAL PROPERTIES

	Physical Properties				Analyses[d] (As-Received)			
			Grindability[c]					
Coal Type	Particle[a] Specific Gravity	Hardness,[b] Mohs	HGI	WI	Moisture Content, wt%	Sulfur Content, wt%	Ash Content, wt%	Gross Heating Value, Btu/lb
Bituminous:	-	0.5-2.5	-	15.2-17.3	-	-	-	-
Eastern	1.1-1.5	-	55-110	-	1-8	0.7-4.0	3-16	11,500-14,500
Midwestern	1.6-1.7	-	45-65	-	2-18	1.0-7.0	6-16	9,500-12,000
Subbituminous	-	-	40-60	-	10-30	0.3-1.0	3-32	6,000-11,000
Lignite:	-	-	-	-	-	-	-	-
Gulf Coast	-	-	50-90	-	20-40	0.4-2.3	7-40	4,300-8,000
Northern Plains	-	-	25-45	-	33-44	0.2-1.4	4-8	6,000-7,500

[a] References 3-6.

[b] Reference 7.

[c] HGI - Hardgrove Grindability Index, References 9-15.
WI - Bond Work Index - dry grinding, References 5 and 8.

[d] References 16-23, metric conversion factor: J/g = Btu/lb x 2.325.

The ash content varies widely for most type coals and is not indicative of coal rank. The Northern Plains Lignites are an exception with a low, narrow-range ash content of less than eight percent. The specific constituents of the ash are as important, if not more important than the total ash content. Ash constituents of various coal types and their influence on furnace slagging and convection pass fouling are discussed later in this section.

Grindability

Some coals are more difficult to pulverize than others. To determine the grindability of coals, five different test methods have been developed over the years.[24,25,26] The methods routinely used by boiler manufacturers for evaluating grindability characteristics of coals depend on coal rank, reproducibility limits, and the degree of confidence in the available testing procedures. For bituminous coals, a test method was developed to determine the grindability in a standard ball-and-race mill relative to a reference coal. This method is called the Hardgrove Grindability Index (HGI). This method is described in ASTM Standard D 409-71. A reference coal is assigned a value of 100. A coal that is more difficult to grind than the reference coal will have an HGI lower than 100.

For lower rank coals the results of the direct Hardgrove test often give misleading data. The problem with determining the grindability of subbituminous and lignitic coals is their high moisture content. For these coals a modified version of the HGI method is more reliable. Several prepared samples are dried to different moisture levels and the grindability is determined at each. The results of such a series of grindability tests showed that the HGI of Texas lignites increases with moisture content. The Colorado bituminous coals tend to decrease in HGI with a moisture level increase. Alternately, the HGIs for subbituminous coals and North Dakota lignites start to decrease, then increase with increased moisture level, with a minimum HGI at around 15 to 25 percent moisture content.[25] The grindability corresponding to the approximate moisture level of the coal in the pulverizer grinding zone is used to determine the required mill capacity. Typically, the grinding-zone moisture level is about 10 percent below the moisture content of the coal fed to the pulverizer.

On some lignites, even this modified HGI has been inaccurate. More accurate data have been obtained with a third test method known as the Continuous Grindability Index (CGI). A laboratory-scale ball-and-race pulverizer is used to measure torque and power requirements, as well as product flow rate and product fineness.

One of the oldest grindability test methods is the Ball Mill Index (BMI).[27] This was the most common method when ball mills were extensively used to pulverize coal. The method was standardized as ASTM D-408.

However, since vertical spindle pulverizers (see Section 6) have almost completely replaced ball mills for coal service, the ball mill test is no longer widely used.

The last indicator of grindability is called the Bond Work Index (WI). Extensive data on this index for numerous materials have allowed rough sizing of crushing and grinding equipment based on the semitheoretical Bond crushing law (see Section 6).

As shown in Table 5-1, the grindability of coals varies over a wide range, but in general grindability decreases with the lower rank coals. The grindability of bituminous coals is affected most by the components of the ash. The hard impurities of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), ferric oxide (Fe_2O_3), and titanium dioxide (TiO_2) tend to decrease grindability. In addition, among the low and medium volatile bituminous type coals, the HGI decreases with the fixed carbon content. The grindability of the western coals is also affected by the high moisture content, as noted in the test method discussions. Lignites are composed of a fibrous material which does not break apart easily during grinding.

Other Properties

Other coal properties that affect the design of the boiler and materials handling subsystems are heating value, particle specific gravity, and hardness. The heating value, on an as-received basis, generally decreases with coal rank. Heating values of lignites are only 50 to 70 percent of those for bituminous coals as shown in Table 5-1. Therefore the materials handling system for a lignite fired boiler must process almost twice as much coal to achieve equivalent boiler production. This high fuel feed rate together with the high fuel moisture content also leads to high flue gas flow rates in a lignite fired boiler thereby affecting the designs of the furnace and convection sections.

The particle specific gravity is important in the design and operation of coal preparation and firing systems. In preparation for firing in boilers, coal is dried, pulverized, and pneumatically conveyed to the burners. The coal specific gravity determines the air flow requirements for conveying systems.

The hardness of materials is measured by several different methods, but the Moh scale is a criterion of its resistance to crushing and grinding. It is also a reasonably good indicator of the abrasive character of coals, which determines wear on the grinding media, and erosion in the pneumatic conveying feed lines to the burners. The hardest ash impurities mentioned under grindability characteristics cause the most severe erosion rates.

COAL ASH PROPERTIES

The tendency of a coal to cause slagging or fouling problems is related to the chemical composition of the ash. Slagging potential is largely a function of the ash melting and viscosity properties. Fouling potential is related to the proportion of volatile ash constituents and the total quantity of ash present in the coal. This section discusses these relationships and presents methods for assessing the coal slagging and fouling potential.

Ash Constituents

Ash is a mineral residue containing Si, Al, Fe, Ca, Mg, and Na, and smaller quantities of P, Ti, K, and various trace elements. Sulfur is also found in coal ash. These elements occur in the ash as a mixture of compounds, but are usually reported as oxides in their highest oxidation state. Since ash is the residue remaining after combustion, its composition varies with combustion conditions and is not the same as the coal mineral content before combustion. Since combustion conditions vary with time and position within a furnace, the ash produced varies in composition and physical properties. Thus, ash coating the furnace walls is different from ash deposited in the convection passes or fly ash.

In order to compare ashes from different coals and predict their relative performance in a boiler, designers rely on the measured properties and composition of ash prepared in the laboratory. This ash is prepared under carefully controlled combustion conditions defined by ASTM[28] to give a reproducible and uniform sample. The properties and composition of this ash sample, together with experience, allow the designers to predict ash performance in the boiler and to design the boiler accordingly.

In Table 5-2 are presented some ranges of laboratory ash compositions measured for coals representing the major U. S. coal types discussed earlier in this section. Some distinguishing features of these compositions are as follows. High rank bituminous coal ash contains considerably larger proportions of SiO_2 and Al_2O_3 than low rank North Dakota lignite. Intermediate rank subbituminous coal contains intermediate proportions of these compounds. The reverse trend is shown with CaO and MgO. For these three coal types, the proportions of CaO and MgO increase with decreasing coal rank.

Texas lignite is an exception. Gulf Province lignites have higher coal ash contents than Northern Plains lignites. These higher ash levels are due primarily to increased quantities of SiO_2 and Al_2O_3. The relative quantities of CaO and MgO expressed as a percentage of dry coal are actually fairly similar for the two lignites. However, these compounds make up a smaller portion of the ash for Texas lignite than for North Dakota lignite.

TABLE 5-2. ASH ANALYSES FOR SOME MAJOR U. S. COAL TYPES[a]

	Bituminous Coals (135 samples)		Montana Subbituminous Coal (# samples unknown)		Texas Lignite (10 samples)		North Dakota Lignite (338 samples)	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Analysis, weight percent of ash:								
SiO_2	48.2	9.3-69.6	35.5	15.1-59.0	46.3	25.2-66.4	20.0	6.3-48.1
Al_2O_3	24.9	5.6-41.7	18.7	8.6-32.1	17.5	12.4-22.7	11.8	4.2-26.1
Fe_2O_3	14.9	3.8-84.2	7.8	1.9-27.8	7.3	1.8-15.4	8.0	1.2-28.5
TiO_2	1.1	0.1-2.5	0.7	0.1-1.8	1.2	0.5-1.6	0.3	0.1-0.7
P_2O_5	NA	NA-NA	0.3	0.0-1.3	0.2	0.0-0.5	0.3	0.0-1.6
CaO	6.6	0.2-36.7	15.6	3.1-45.7	12.6	3.8-20.5	26.3	11.7-52.0
MgO	1.7	0.4-6.3	4.4	0.2-11.4	2.6	0.4-6.1	7.2	2.8-13.6
Na_2O	1.2	0.0-7.6	1.7	0.1-10.6	1.1	0.2-4.5	6.9	0.2-27.8
K_2O	1.5	0.1-6.0	0.4	0.0-2.2	0.7	0.1-1.8	0.3	0.1-1.7
SO_3	NA	NA-NA	13.4	2.0-23.0	9.6	2.6-19.0	17.2	5.2-32.0
ASTM softening temperature:								
°C	1,290	1,060-1,610	1,200	1,060-1,590	NA	NA-NA	1,272	1,080-1,500
°F	2,355	1,940-2,930	2,200	1,940-2,890	NA	NA-NA	2,322	1,970-2,730

NA - Not available.

[a] Data reported by U. S. DOE Grand Forks Energy Technology Center, references 29 and 30.

Bituminous coal ash contains a larger proportion of Fe_2O_3 than lower rank coal ashes. This feature is used by boiler designers to distinquish between two major ash types. A coal ash is considered a "bituminous type" ash if the quantity of Fe_2O_3 is greater than the combined quantities of CaO and MgO. Other coal ashes are considered as "lignite type" ashes. Notice that by this definition subbituminous coal ash is considered a lignite type ash.

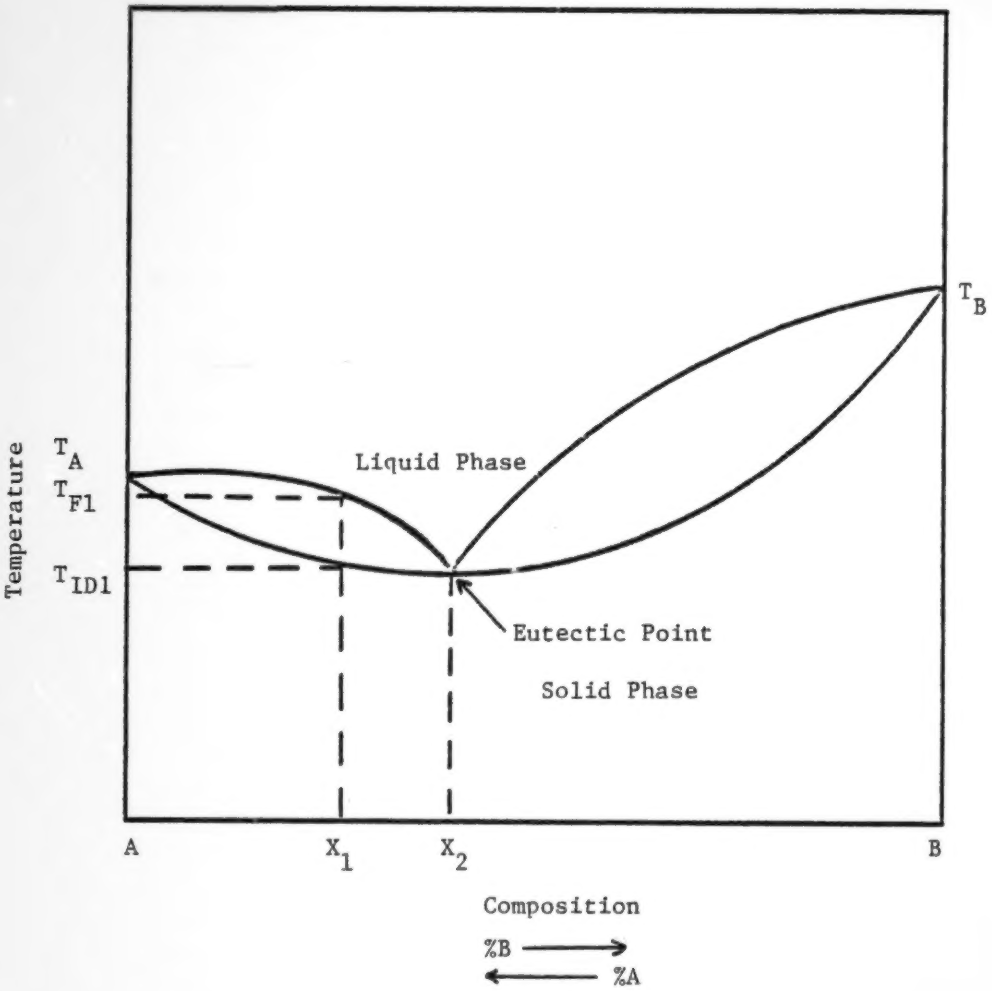
Ash Influence on Slagging

Ash constituents affect melting and viscosity properties which in turn affect coal slagging potential. This subsection discusses these relationships and presents some parameters for assessing coal slagging potential.

In addition to ash compositions, Table 5-2 also presents ranges in a parameter called the ash softening temperature. This parameter is one of several types of fusion temperature measurements conducted on laboratory ash and used by boiler designers as an indication of the melting properties of furnace ash. Procedures for these measurements are defined by ASTM[31] and consist of heating small cones of ash under controlled conditions. The following temperatures are determined:

1. Initial deformation temperature - when the first rounding of the tip of the cone occurs,
2. Softening temperature - when the cone has melted to a point that its height is equivalent to its base (sometimes called the spherical softening temperature),
3. Hemispherical temperature - when the cone height is reduced to 1/2 its base (sometimes called the hemispherical softening temperature), and
4. Fluid temperature - when the cone has spread out into a flat layer no higher than 0.16 cm (1/16 inch).

Because it is a multicomponent mixture, coal ash has a range of melting temperatures as indicated by these fusion temperatures. Winegartner and Ubbens[32] explain that an idealized two component phase diagram is useful for understanding the melting behavior of coal ash. Such a diagram is presented in Figure 5-3. This diagram illustrates the range of temperatures from initial deformation to fluid for composition X_1 which is a mixture of pure components A and B. It also illustrates that changes in the composition of the mixture also change the absolute values of the fusion temperatures and the spread between them. Mixture X_2 represents a eutectic. At this point fusion temperatures are at their lowest levels and the spread between them is very small.


Temperature
T_A
T_{F1}
T_{ID1}
T_B
Liquid Phase
Eutectic Point
Solid Phase
A
X_1
X_2
B
Composition
%B →
← %A

Legend: T_A = melting temperature of pure component A
T_B = melting temperature of pure component B
X = mixture of pure components A and B
T_{ID1} = initial deformation temperature of mixture X_1
T_{F1} = fluid temperature of mixture X_1

Figure 5-3. Idealized two component phase diagram for explaining ash melting behavior.

Coal ash behaves somewhat similarly though the situation is complicated by an increased number of components. One such complication is introduced by the presence of iron, which strongly affects slag behavior depending on its oxidation state - FeO or Fe_2O_3. Since oxidizing and reducing conditions both exist within a furnace, ash fusion temperatures are commonly determined under both conditions. In practice, fusion temperatures determined under reducing conditions are lower - especially for ashes with a substantial iron content. The term "ash softening temperature" usually refers to the spherical softening temperature determined under reducing conditions.

Boiler designers have found the slagging tendency of coal ash within the furnace to be related to the measured fusion temperatures of laboratory ash. The lower the fusion temperatures the greater the slagging tendency. Also important is the spread between the fusion temperatures. Ash with a narrow spread is more likely to result in a running slag on the furnace walls. Preventing this phenomenon is very important in a dry bottom furnace design. Otherwise, the slag may collect in the cooler ash hopper zone and freeze into large deposits plugging the hopper opening.

Another important coal ash physical property is its viscosity-temperature relationship. All modern boilers are designed to operate with some degree of slag accumulation on the furnace walls. This is not due to choice but to practical furnace design limitations. The degree of accumulation is dependent on the ash fusion characteristics and temperature - the latter a function of boiler design. The behavior of the slag is governed by its viscosity characteristics. The lower the slag viscosity the more likely it is to run.

The viscosity of coal ash is very difficult to measure. However, viscosity - temperature relationships can be estimated based on ash composition and fusion temperatures.[32] In general, for similar ash analyses, changes in composition which decrease the fusion temperatures also decrease the slag viscosity.

As shown in Table 5-2 the measured range of ash softening temperatures does not vary greatly with coal type. However, the influence of ash constituents on softening temperature does vary by type. Figure 5-3 is again useful for understanding these influences. This two-component analogy can be used by separating the ash constituents into two groups - acids and bases. The acids are represented by SiO_2, Al_2O_3, and TiO_2; the bases by Fe_2O_3, CaO, MgO, Na_2O, and K_2O.

If A represents the acid constituents and B the bases, this figure qualitatively shows the effect of altering the proportions of acids and bases. A bituminous coal contains a larger proportion of acids than bases and could be represented by mixture X_1. Increasing the proportion of basic constituents for this type of coal reduces the fusion temperatures and the spread between them. On the other hand, lower rank coals are commonly located further to the right hand side of the diagram. For these coals, increasing the proportion of basic constituents increases the fusion temperatures.

A common ash parameter used by boiler designers to compare different coals is called the base-to-acid ratio. This parameter is simply a ratio of the quantities of basic constituents to acidic constituents (usually expressed on a weight basis) as defined below.

$$B/A = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2} \qquad (5\text{-}1)$$

DOE[33] has plotted fusibility data for a large number of coals with bituminous and lignite type ash. These data indicate that the lowest fusibility temperatures, represented by mixture X_2 in Figure 5-3, tend to fall in the range of 35 to 55 percent basic constituents. This corresponds to a B/A ratio range of 0.5 to 1.2. Babcock and Wilcox[34] (B&W) confirms that a coal ash with a B/A ratio in this range is likely to cause slagging problems. Combustion Engineering[35] also reports that higher slagging potentials are common for coals with B/A ratios between 0.2 and 0.7.

The B/A ratio is related to the ash fusion temperatures because it is an indication of the potential for ash constituents to combine to form low melting salts. Very low or high B/A ratios reflect lower potentials for this occurrence. However, since all acids and all bases are not equal, B/A ratio does not tell the whole story. For example, substantial quantities of sodium or potassium can reduce ash melting temperatures regardless of B/A ratio. Thus, boiler designers also consider some other ash parameters together with B/A ratio as indicators of slagging potential. Some of these are mentioned below.

Combustion Engineering[35,36] reports the iron/calcium ratio (Fe_2O_3/CaO) to be important. Although both components are bases, they interact to reduce fusibility temperatures. These effects are most evident at ratios between 3 and 0.3. As an example, lignite type ashes usually have iron/calcium ratios of less than 1.0 and fusibility temperature decreases as the ratio approaches 1.0.

Babcock and Wilcox[34] reports using several indices to compare the slagging potential of various coals. For bituminous coals B&W defines the following slagging factor:

$$R_s = (B/A) \; * \; S \qquad (5\text{-}2)$$

where S is the percent sulfur in the dry coal analysis. The higher the value of R_s the more likely the coal is to cause slagging problems.

As discussed earlier, increasing the proportion of basic constituents in a bituminous coal reduces the ash fusion temperatures. In bituminous coals the percent sulfur is closely related to the pyritic iron content, which in its reduced form, further lowers ash fusion temperatures.[32] This index is not valid for lower rank coals, however. For these coals B&W prefers indices based on the ash fusion temperatures or on the viscosity - temperature relationship where this information is available. Further information on these indices is provided in the literature.[34]

Boiler designers also consider various ash parameters that are empirically correlated with slag viscosity and thus affect slag behavior. For high base coals the dolomite ratio or percentage as defined below is considered important.

$$\text{Dolomite Ratio} = 100 * \frac{CaO + MgO}{\text{Total Base}} \qquad (5\text{-}3)$$

Increases in dolomite ratio increase slag viscosity for high base coals. For high acid coals, increases in the silica/alumina ratio (SiO_2/Al_2O_3) increase slag viscosity.

Ash Influence on Fouling

Various ash constituents also affect the potential for fouling in the convection passes. This subsection discusses these relationships and presents some parameters for assessing the coal fouling potential.

With low rank coals containing high alkali ash the primary ash constituent contributing to fouling is sodium. Sodium compounds cause problems because of their low melting and sublimation temperatures. Most sodium compounds melt at temperatures below 900°C (1650°F). Obviously, molten compounds are likely to stick to convection pass tube surfaces. However, the sublimation properties of sodium compounds are probably a more important contributor to fouling. Sodium is organically bound in the matrix of low rank coals. This sodium has a high potential for forming sodium oxide and vaporizing in the combustion zone. The temperature at which sodium oxide is converted directly from a solid to a gas is 1290°C (2350°F).

Sodium compounds volatilized in this manner are easily dispersed in the gas stream. As the combustion gases cool, these compounds condense on other ash particles and tube surfaces. The sodium reacts with the ash particles and other flue gas constituents, binding the particles together and causing deposit buildup.

Coal ash content and flue gas temperature also affect the severity of ash fouling with low rank coals. Higher ash coals are more prone to fouling than are lower ash coals. Fouling is also exacerbated by high flue gas temperatures in the convection section. With higher temperatures more volatilized compounds are present in the gas stream and available for condensation on cooler tube surfaces. Also, ash particles in the gas stream are more likely to be softened and prone to sticking on tube surfaces.

Based on power plant operating experience and field and pilot plant test results, DOE[37] has consolidated these factors in a set of parameters describing the fouling potential of low rank coals. These parameters are presented in Table 5-3. A simpler though less precise fouling index for low rank coals, reported by Babcock and Wilcox,[38] is presented in Table 5-4. This index is based entirely on the ash sodium content. Two other coal ash constituents identified by DOE as affecting fouling in low rank coals include silica and calcium oxide. Silica increases fouling while calcium oxide appears to decrease it.

Volatile sodium is also a key contributor to fouling with bituminous coals - even at levels as low as two percent of the ash. With these coal types iron and sulfur combine with the sodium to form deposits consisting of complex alkali-iron sulfates.[39] These deposits are usually tightly bonded and more dense than the deposits resulting from low rank coals.

Alkalies (sodium and potassium) are present in the coal in two forms - silicates and chlorides. The silicates are not considered volatile and tend to retain the alkalies in the ash. Chlorides, on the other hand, are volatile. As a result, the coal chlorine content has come to be used as an index of the volatile alkalies content and of the fouling potential. A chlorine content fouling index for bituminous coals reported by Combustion Engineering[39] is shown in Table 5-5. Another fouling index for bituminous coals, reported by Babcock and Wilcox,[40] is presented in Table 5-6.

LIMESTONE TYPES

Limestone is a general term applied to sedimentary carbonate rocks or fossils. In contrast, marbles are metamorphic rocks resulting from recrystallization of limestone and are hard enough to be polished. Limestone is composed primarily of calcium carbonate ($CaCO_3$) or combinations of calcium and magnesium carbonate ($MgCO_3$) with varying amounts of impurities. Classification and minerology of limestones establishes six types as listed below:[41,42]

- Aragonite,
- Calcite,
- Chalk,
- Dolomite,
- Marl, and
- Vaterite.

Aragonite is a mineral form of $CaCO_3$ with an orthorhombic crystalline structure. It is a rare limestone and is structurally only meta-stable.

TABLE 5-3. FOULING POTENTIAL OF LOW RANK COALS AS A FUNCTION OF MAJOR CONTRIBUTING FACTORS[c]

	Percent Na in Dry Coal or (Percent Na_2O in Ash)		
	<0.1 (<1)	0.1-0.5 (1-5)	>0.5 (>5)
Percent Ash in Dry Coal[a]			
<4	low	low	low-medium
4-8	low	low-medium	medium-high
>8	low	medium-high	high
Flue Gas Temperature[b] °C (°F)			
<870 (<1600)	low	low	low
870-1040 (1600-1900)	low	low-medium	medium
>1040 (>1900)	low	medium	high

[a] Flue gas temperature held constant at 1040°C(1900°F).

[b] Ash content held constant at 8 percent.

[c] This information was developed and reported by researchers from the DOE Grand Forks Energy Technology Center[37] and applies to Western and Gulf Province low rank coals.

TABLE 5-4. FOULING INDEX FOR LOW RANK COALS REPORTED BY BABCOCK AND WILCOX[a]

Fouling Potential	% Na_2O in Ash
low to medium	3
high	3-6
severe	6

[a] Reference 38.

TABLE 5-5. FOULING INDEX FOR BITUMINOUS COALS REPORTED BY COMBUSTION ENGINEERING[a]

Fouling Potential	Percent Cl in Coal
Low	<0.15
Medium	0.15 - 0.30
High	>0.30

[a] Reference 39.

TABLE 5-6. FOULING INDEX FOR BITUMINOUS COALS REPORTED BY BABCOCK AND WILCOX[a]

$R_f = B/A * Na_2O$[b]

Fouling Potential	Fouling Index, R_f
Low	<0.2
Medium	0.2 - 0.5
High	0.5 - 1.0
Severe	>1.0

[a] Reference 40.

[b] Weight percent Na_2O in ash.

Aragonite irreversibly changes to calcite if heated to 400°C (750°F) or if free moisture is present.

Calcite is a mineral form of $CaCO_3$ with rhombohedral crystalline structure. It is the most common type of high-calcium limestone. There are at least four common sources of calcite: coral, fredonia, oolitic, and shell. Coral calcite, as the name implies is a fossiliferous limestone from coral. Fredonia limestone is from a large deposit in Kentucky. Oolitic limestone consists of small rounded grains or pellets (oolites) deposited in concentric laminates around a nucleus of $CaCO_3$ or a sand particle. Deposits are found mainly in Indiana and the Bahama Islands. Shell is derived from clam and oyster shells.

Chalk is a soft, friable, fine-grained limestone consisting primarily of the remains of minute marine organisms. It varies in color, hardness, and purity. White chalks may have a $CaCO_3$ content of 98 to 99 percent; gray chalks contain as much as 20 percent impurities. Chalks are reported to be easier to grind than other limestone types.

Dolomite is a type of limestone which contains more than about 20 percent $MgCO_3$. The mineral "dolomite" is a mixture of about 55 percent $CaCO_3$ and 45 percent $MgCO_3$ by weight, present in a rhombohedral structure.

Marl is an indefinite term used to describe a loose, soft, impure material which contains fine-grained fragments of shell and marine organisms intermixed with clay and other impurities. Sand or silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3) content may be very high.

Vaterite is a mineral form of $CaCO_3$ with amorphous crystalline structure. It is structurally unstable and converts to calcite at higher temperatures or saturated moisture conditions. It occurs only in small, scattered deposits and is of no commercial significance.

Limestone deposits occur in virtually every state of the U. S. However, in some cases they may be lodged too deeply or intricately in the earth to be practically mined or located relatively far from boiler locations. A geological map of available high-calcium limestone and chalk deposits is presented in Figure 5-4. Most of the calcium carbonate deposits and "active" quarries are located in the Appalachian and midwestern parts of the U. S. Coal-fired boilers in coastal areas or in parts of the West may be located relatively far (a few hundred miles) from available high-calcium deposits. In some coastal locations shellfish operations may provide a supply of calcium carbonate. Another possible source for coastal locations is a large "active" deposit of oolitic aragonite in Bermuda. Major deposits of chalk are located in Alabama, Arkansas, Kansas, Mississippi, Nebraska, South Dakota, Tennessee, and Texas. Deposits of dolomite are abundant in Minnesota and Wisconsin, but little high-calcium limestone is available there.

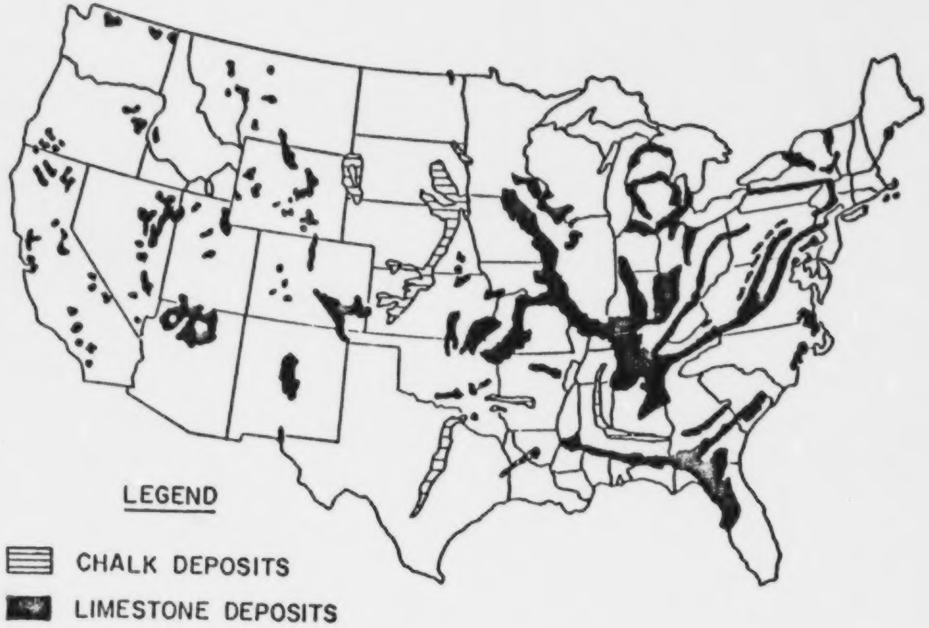

LEGEND
▤ CHALK DEPOSITS
■ LIMESTONE DEPOSITS

Figure 5-4. High-calcium limestone and chalk deposits in the United States.[a]

[a] Reprinted from reference 43.

LIMESTONE PROPERTIES

Limestone chemical composition, grindability, and other limestone physical and chemical properties affect the application of LIMB to pulverized coal boilers through their influence on materials handling equipment design and SO_2 control.

Composition

The limestone composition is important through its effects on SO_2 control and other limestone physical properties. The range of U. S. limestone compositions is presented in Table 5-7.

The calcium content ranges from as low as 60 percent to over 99 percent for high-calcium limestone. The calcium content of dolomites can be much lower. Magnesium carbonate is present in almost all limestones. Most marls and chalks are of relatively poor chemical quality. They generally contain only 82 to 90 percent total carbonates. While other physical and chemical factors also affect SO_2 control, the total quantities of reactive calcium and magnesium compounds are important since these compounds are responsible for sulfur capture and determine the limestone injection rate.

There are three major impurities in limestones: silica, alumina, and iron. These compounds increase limestone weight without contributing directly to SO_2 control. Also, large quantities of these compounds increase grinding energy requirements. Silicon dioxide ($Si0_2$) is usually the largest impurity and aluminum oxide (Al_20_3) is the next most significant. Ferric oxide (Fe_20_3) is usually present in concentrations less than 1.5 weight percent. Phosphorous and sulfur usually occur, but generally in concentrations less than 0.5 percent. Trace impurities include manganese, copper, titanium, sodium and potassium (as oxides), flourine, arsenic, strontium, and others. Organic matter, usually under one percent, is also often present.

Moisture content varies widely among the limestone types as shown in Table 5-8. Other limestone properties are also listed in the table. Moisture content is important since all moisture must be evaporated either in the limestone grinding system or in the boiler. In either case, this results in an overall system latent heat energy loss. Generally, high calcium limestones and chalks are very porous and water absorbent; moisture contents of up to 20 percent are common. Marls are the most water absorbent type of limestone. Moisture contents of up to 55 percent are not uncommon with this type.

Grindability

Limestone grindability can be determined by the same test methods used for coal. However, only limited limestone grindability data are available in the literature. Some reported grindability data obtained

TABLE 5-7. RANGE OF LIMESTONE AND DOLOMITE COMPOSITIONS IN U. S.[a]

Location	$CaCO_3$	$MgCO_3$	SiO_2	$Al_2O_3 + Fe_2O_3$
Alabama	82.3–98.4 55.0	4.0–0.5 43.0	7.9–1.0 1.0	4.1–0.8 1.0
Arkansas	95.0	-	-	-
Colorado	96.0–98.0	0.5–2.5	-	-
Florida	85.0–98.0	10–0.6	-	-
Georgia	89.9–99.1 55.0	5.1–1.0 36.0	2.8–0.7 3.0	1.8–0.8 1.0
Illinois	86.7–98.9	6.5–0.5	-	-
Indiana	85.0–98.9	8.9–0.6	-	-
Iowa	56.6–99.4	1.6–0.1	-	-
Kansas	88.0–97.1	1.0–0.5	-	-
Kentucky	80.6–99.5	4.2–0.1	7.8–0.3	2.9–0.1
Maine	95.6	1.0	-	-
Maryland	62.9–97.4 1.2–56.7	3.3–1.8 96.6–40.8	20.3–1.1 4.3–1.8	10.0–0.7 0.8–1.2
Michigan	90.0	4.4	-	-
Minnesota	88.8–95.7	1.1–2.8	-	-
Missouri	85.0–98.0	10.1–1.0	-	-
Nebraska	89.7–98.0	5.0–0.0	-	-
New Jersey	90.0	4.0	-	-
New York	92.0–98.2	3.3	-	-
North Carolina	94.0–95.4 55.0	- 40.0	- 1.0	- 0.2
Ohio	70.3–96.4 48.5–53.8	15.9–0.8 39.5–45.0	5.8–0.7 7.3–0.4	4.5–0.9 2.5–0.3
Oklahoma	88.0–95.0	2.0–1.0	-	-
Pennsylvania	66.8–98.5 44.7–55.9	13.0–0.2 38.1–34.7	11.4–0.5 21.6–6.2	6.2–0.6 4.1–2.0
Rhode Island	95.0	-	-	-
South Carolina	94.0	1.5–3.6	-	-
South Dakota	96.0	-	-	-
Tennessee	74.1–99.0 49.2–67.4	12.7–0.3 4.6–22.7	11.7–0.5 40.8–8.7	1.5–0.2 5.5–1.3
Texas	95.0–98.2	2.2–0.4	-	-
Vermont	95.0–98.6	0.5	-	-
Virginia	82.0–97.8 50.9–56.7	9.7–1.0 40.9–40.8	4.1–0.3 5.9–1.8	4.7–0.8 1.1–1.2
Washington	95–99	1.0–0.8	-	-
West Virginia	68.3–99.4 50.1–59.6	13.8–1.1 17.3–20.2	19.9–0.3 23.2–11.5	2.7–0.1 7.4–6.1
Wisconsin	95.6–97	-	-	-
Wyoming	97.6–98.4	0.9–0.2	-	-

[a] Data compiled from references 44 and 45.

TABLE 5-8. LIMESTONE PROPERTIES

Limestone			Particle[a] Specific Gravity	Bulk[b] Density lbs/ft^3	Hardness,[c] Mohs	Grindability[d]			Moisture[e] Content,%
						HGI	BMI	WI	
Aragonite $CaCO_3$			2.94	-	3.5-4.0	-	-	-	-
Calcite $CaCO_3$			2.72	-	3.0	-	-	-	-
High Ca Limestone			1.8-2.9	85-185	2.0-4.0	-	-	13.6-17.0	1-20
Chalk			1.4-2.0	85-150	-	-	-	-	2-20
Calcium oxide CaO			3.2-3.4	-	-	-	-	-	-
Magnesite $MgCO_3$			3.0	-	3.5-4.5	-	-	22.5	-
Dolomite $CaMg(CO_3)_2$			2.83	90-100	3.5-4.0	-	-	15.1	-
Examples: (Dry Basis)									
Ref.	$CaCO_3$,%	$MgCO_3$,%							
58,59	93.0	1.0	-	-	-	70.5	-	-	-
60	91.8	3.1	-	150	3.0	50-57	-	-	10.0
61	95.0	1.7	2.67	-	-	-	-	-	2.0
	95.7	1.0	2.49	-	-	-	-	-	1.5
	82.1	5.0	-	-	-	-	-	-	4.7-55.0
62	52.3	43.0	-	-	-	-	19	-	-
	85.8	9.4	-	-	-	-	10	-	-
	69.8	27.9	-	-	-	-	12	-	-

[a] References 47-51.

[b] References 47-50.

[c] References 52 and 53.

[d] HGI - Hardgrove Grindability Index
BMI - Ball Mill Index
WI - Bond Work Index - dry grinding, References 54 and 55.

[e] Reference 56 and 57.

in this study were Hardgrove (HGI), Ball Mill (BMI), and Bond Work (WI) indices. While one source[46] reported testing many limestones with HGI ranging from a low of 40 to over 160, most limestones are expected to be in the HGI range of 60 to 80. Reported values for all three grindability indices are presented in Table 5-8. As for coals, moisture content and impurities greatly affect the grindability of limestones.

Other Properties

Various other limestone properties are also important for application of LIMB. These include particle specific gravity, hardness, bulk density, and reactivity for sulfur capture.

As discussed for coal, the specific gravity of the limestone particle determines the amount of conveying air required for injection. Comparison of values in Tables 5-1 and 5-8 show that most limestones are about two to three times more dense than coals. Lower density chalks have specific gravities slightly less than or equal to that of some coals.

The hardness properties determine grindability and erosion potential. Comparison of values in Tables 5-1 and 5-8 shows that oolitic, aragonite, and calcite tend to be slightly more abrasive than coals. Marl and chalks tend to be softer than most coals.

The bulk density of limestone is important in sizing the material handling system. Bulk densities, presented in Table 5-8 vary over a wide range because of inherent differences in porosities of the natural stones.

A final important property is the "reactivity" of limestone in reactions with sulfur compounds. Limestone reactivity influences the amount of limestone required to get the desired SO_2 control. Other portions of the EPA program are addressing the fundamental aspects of sulfur capture with LIMB. However, a few general comments follow.

The reactivity of the limestone for sulfur capture may depend on the sulfur capture mechanism. Conventional sulfur capture by limestone injection under oxidizing conditions involves calcination of the limestone followed by reaction with sulfur oxides as shown by the following generalized reactions.

$$CaCO_{3(s)} \longrightarrow CaO_{(s)} + CO_{2(g)} \qquad (5\text{-}4)$$

$$CaO_{(s)} + SO_{2(g)} + \tfrac{1}{2}O_{2(g)} \longrightarrow CaSO_{4(s)} \qquad (5\text{-}5)$$

Under the reducing conditions associated with LIMB, another reaction mechanism may occur which involves direct reaction of limestone with H_2S or other sulfur compounds.

$$CaCO_{3(s)} + H_2S_{(g)} \longrightarrow CaS_{(s)} + H_2O_{(g)} + CO_{2(g)} \qquad (5\text{-}6)$$

Typically in gas-solid reactions, the reaction rate depends on the available reactive surface area. Chemical purity of the solid particles could have some effect, but generally the most important factors are the particle physical characteristics - particle size and pore volume. Decreased particle size and increased pore volume provide greater surface area for reaction. Particle size is a function of grinding equipment design. Pore volume is probably a function of limestone type and injection conditions.

In some previous tests[63] conducted under oxidizing conditions, the softest, finest-grained limestone types (chalks and marls) showed significantly higher reactivity for SO_x than other limestones, even those of greater chemical purity. Under the conventional oxidizing sulfur capture mechanism, high limestone particle temperatures may result in "deadburning" or a loss in reactive surface area. Some limestone types are probably more susceptible to deadburning than other types. Test methods are available to determine this susceptibility.[64]

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SECTION 6

LIMESTONE HANDLING AND PREPARATION

This section discusses the design considerations for handling raw limestone and its preparation for injection into the furnace of pulverized coal fired boilers. A generalized discussion of the impact of limestone injection on the boiler net electrical power output is presented. The influences of several boiler operating approaches are discussed. Also, a discussion of the limestone injection rate required for a range of coal types and boiler sizes is presented. The required equipment and electrical power consumption for the materials handling and limestone preparation systems are presented.

LIMESTONE INJECTION IMPACTS

In order to design a limestone injection system, the amount of limestone required must be determined. The limestone feed rate can vary depending on several variables. However, the amount of limestone usage will be in direct proportion to the coal firing rate.

The coal firing rate depends on the coal type and heating value as discussed in Section 5, the boiler size, and the boiler overall net power output efficiency. Limestone injection impacts the net power output by consuming electrical power for handling the sorbent and by reducing the thermal efficiency of the boiler. Thermal efficiency effects are discussed in Section 9. Thus, the coal firing rate depends on how the boiler is operated in response to these influences on the net power output. During limestone injection, the net power output, rated in electrical megawatts (MW_e net), will be equal to the boiler base rating without limestone injection (MW_e rating) minus the electrical power required for material handling (E_m), limestone preparation and injection (E_p), and the thermal losses (expressed as a power equivalent) due to sorbent injection and reaction (E_t). These impacts can be presented in the following equation:

$$MW_e \text{ net} = MW_e \text{ rating} - E_m - E_p - E_t \qquad (6\text{-}1)$$

Altered power requirements of downstream emission control systems are not included in this analysis.

Boiler Operating Approaches

This subsection discusses three possible approaches to operating the boiler with limestone injection. One approach is to minimize capital investment which may require a reduction in the coal firing rate to allow handling of the limestone in the existing coal preparation system. Another approach is to maintain the coal firing rate. A third approach is to maintain the net power output of the boiler.

Approach A: Minimize Capital Investment--

A minimum capital investment would require the limestone to be handled with the coal by the existing receiving, transfer, storage, preparation, and coal firing equipment. However, unless the existing handling system has excess capacity, the coal use rate would have to be reduced to allow for the limestone capacity. This would result in the lowest coal firing and limestone injection rates of the three approaches and in the lowest boiler net power output.

Approach B: Maintain Coal Firing Rate--

To maintain the coal firing rate, a separate limestone handling and preparation system would be required in many cases. Obviously, if the existing coal pulverizers need to be fully utilized to fire the boiler at the base rating, then no significant quantity of limestone can be mixed with the coal. However, if the existing coal handling system has sufficient excess capacity for the limestone, then the base coal firing rate can be maintained without additional pulverizer capacity. The simultaneous grinding of coal and limestone might have the effects of: a change in the pulverizer grinding efficiency, an increase in the pulverizer maintenance, and a decrease in reliability because of incompatible coal/limestone properties. In either case, there would be a slight boiler derating because of the various electrical and thermal energy losses associated with limestone injection. However the derating would be less than with the previous approach.

Approach C: Maintain Net Power Output--

To maintain the net power output of the boiler with limestone injection, the coal firing rate must be increased. The higher firing rate would offset the energy consumption for handling, injection, and utilization of the sorbent and the increased thermal losses. However, when more coal is fired, proportionately more limestone must be added to compensate for the sulfur content of the extra coal. The comparative impact on the boiler would be the requirement for handling the largest coal and limestone quantities of the three approaches, assuming the furnace can handle the increased coal firing requirement.

As with the previous approach this approach would likely require a separate limestone handling and preparation system. Also, some excess coal pulverizer capacity would be needed for the extra coal firing requirement. If the pulverizers do not have any excess capacity, several possible options are available to retrofit the coal preparation system. First, if available, a coal with a higher heating value could be fired. The higher heating value would allow less coal firing to achieve the desired power output, and therefore a smaller coal handling and preparation system capacity. Another option is to use a coal with a higher grindability index (see Section 5). For example, a change in only five HGI units can in some cases increase pulverizer capacity by at least 5 percent (see Grinding Mill Sizing, later in this section). As a third option, pulverizer capacity can be increased about 2 percent for a 2 percentage point decrease in the coal particle size specification. This option would be feasible provided that boiler performance (combustion efficiency and slagging) is not significantly impacted. A fourth option is to upgrade existing pulverizers, such as by adding larger motors. A final option is to install an additional pulverizer to handle both the limestone and extra coal required.

Limestone Injection Rate

The amount of raw limestone required for furnace injection in pulverized coal fired boilers depends on several variables, including:

- coal firing rate,
- coal sulfur content,
- limestone composition,
- calcium-to-sulfur molar ratio requirements, and
- rate of recycle of reactive calcium compounds.

Each of these variables can have a wide range of values. A discussion on variation in the coal firing rate during limestone injection has already been presented. Discussions of ranges in the coal sulfur content and limestone composition were presented in Section 5. This subsection discusses the two remaining variables and their influence on typical limestone feed system handling rates.

Calcium-to-Sulfur Ratio--

As presented in Section 5, the sulfur capture reaction stoichiometry is one mole of calcium per mole of sulfur. Complete utilization of the sorbent has not been achieved in any dry injection tests to date. Calcium utilization appears to be a function of at least the sorbent particle size, the sorbent reactivity, the furnace temperature profile, available residence time for reaction, and the SO_x gas concentration. Past tests have shown that SO_x removal efficiency increases as the calcium-to-sulfur (Ca/S) molar ratio is increased. In addition, coals with lower sulfur contents have required higher Ca/S ratios to achieve equivalent SO_x removal efficiencies because of the lower gas concentrations of SO_x and limestone particles. For a given coal sulfur content, higher Ca/S ratios require higher limestone feed rates.

Boiler Sizes and Coal Types--

The limestone feed rate, regardless of coal type, is determined by the following equation, assuming no recycle of unreacted calcium oxide (CaO):

$$LS = \frac{F * Ws}{Ms} * \frac{R * Mc}{Wc} \qquad (6\text{-}2)$$

where, LS = limestone injection rate, g/hr (lb/hr)
F = coal firing rate, g/hr (lb/hr)
Ws = weight fraction of sulfur in coal, as received
Ms = molecular weight of sulfur, 32.1 grams/g-mole (lbs/lb-mole)
R = Ca/S molar ratio
Mc = molecular weight of $CaCO_3$, 100.1 grams/g-mole (lbs/lb-mole)
Wc = weight fraction of $CaCO_3$ in limestone, as received

The first group on the right side of Equation (6-2) represents the molar feed rate of sulfur. The second group is the conversion to moles of sorbent and quantity of limestone required. The weight fractions used in Equation (6-2) are on an as-received or wet basis to account for moisture content.

Equation (6-2) can be rearranged to allow the use of a specific injection rate factor, T, denoting the total moles of $CaCO_3$ required per unit mass of coal fired, as follows:

$$LS = \frac{F * Mc}{Wc} * T \tag{6-3}$$

where, $T = \frac{Ws * R}{Ms}$

A generalized graph of this specific total injection rate factor is presented in Figure 6-1 for a range of coal sulfur contents and Ca/S molar ratios.

Utility boilers range in size from about 50 to 1300 MW_e ratings. The range of coal types fired is discussed in Section 5. Some example limestone injection rates for boilers firing representative high and low sulfur coals is presented in Table 6-1. The limestone composition is representative of an average high calcium limestone with a 10 percent moisture content (see Section 5). No recycling of unreacted CaO is assumed. To achieve the same SO_x removal efficiency, a higher Ca/S ratio is assumed for the low sulfur coal case, as previously explained.

The calculated injection rates are much higher for the high sulfur coal, even with the lower Ca/S ratio. From these example cases, it is shown that the injection rate can vary from about 8 to 30 percent of the coal firing rate. Even lower limestone injection rates may be allowable with low sulfur eastern bituminous coals since the higher heating value allows a lower coal firing rate than for the subbituminous coal used in the example. Conversely, coals with more than four percent sulfur can require higher limestone injection rates than that shown for the midwestern bituminous coal.

Recycle of Reactive Calcium Compounds--

Calcium oxide (CaO) that does not react in the furnace would be carried along in the flue gas and collected with the fly ash from coal fired boilers. Raw limestone handling could be significantly reduced if

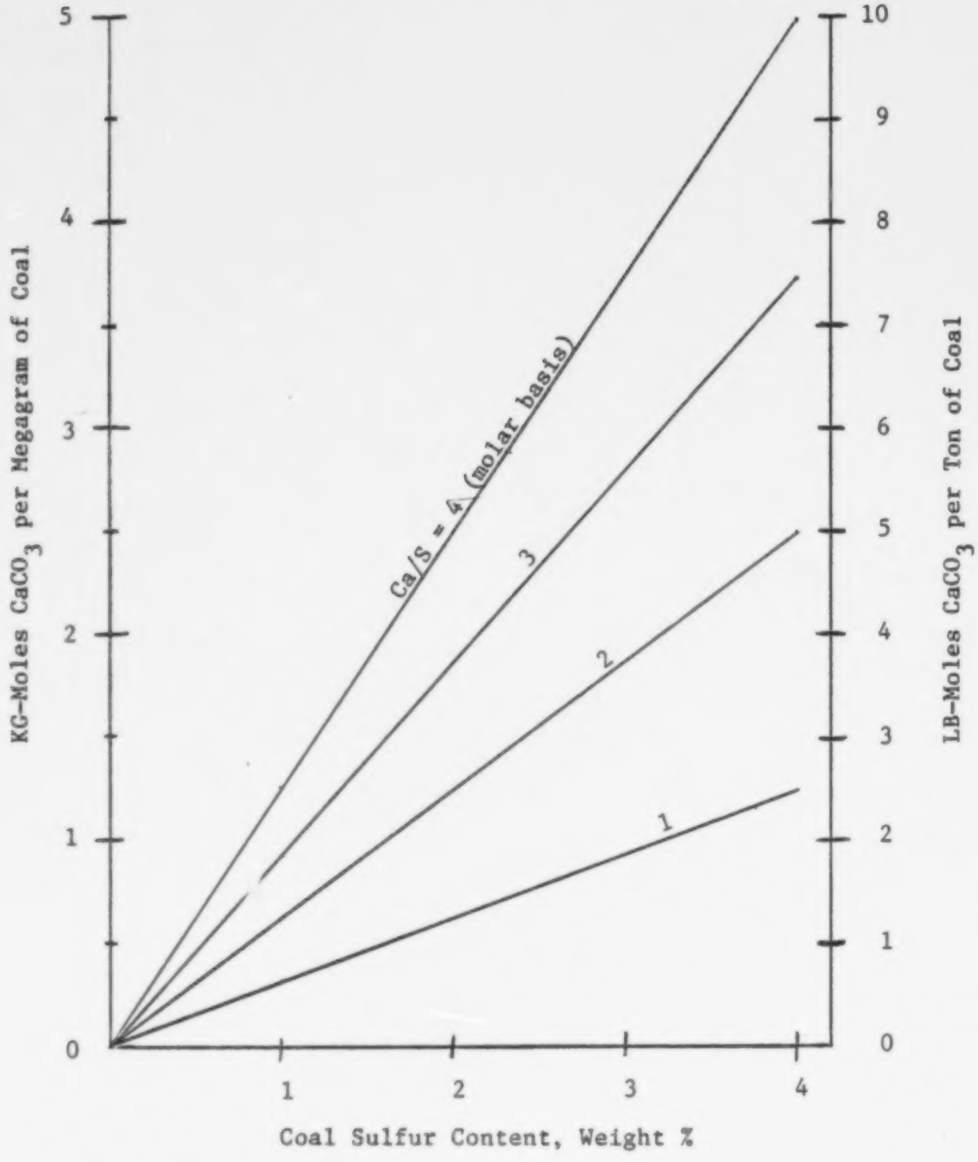

Figure 6-1. Calcium carbonate ($CaCO_3$) sorbent injection rate factor.

TABLE 6-1. LIMESTONE INJECTION RATES FOR BOILERS FIRING HIGH AND LOW SULFUR COALS[a]

Boiler Rating, MW_e		50	500	1300	
Coal	Ca/S	Limestone, Mg/hr (tons/hr)			$\frac{\text{Limestone}}{\text{Coal}}$, %
Montana Subbituminous 0.6% sulfur HHV = 19,930 J/g (8,570 Btu/lb)	4	2.4 (2.6)	24 (26)	62 (68)	8.8
Illinois Bituminous 4.0% sulfur HHV = 23,480 J/g (10,100 Btu/lb)	2	6.5 (7.2)	65 (72)	170 (187)	29.2

[a] Basis: - Boiler coal-to-electric heat rate assumed to be 10.5×10^6 J/kWh (10,000 Btu/kWh)
- Limestone assumed to contain 85.5% $CaCO_3$ on a wet basis (94% on a dry basis)
- No recycling of unreacted CaO

[b] Mg = megagrams

some of the unreacted sorbent could be recovered and recycled to the furnace.

The potential for furnace injection of recovered sorbent may have several limitations. First, increased conversion or utilization of the fresh limestone feed on a once through basis reduces the effectiveness of recycling recovered sorbent. Also, the unreacted sorbent would be collected with spent sorbent and the normal fly ash. The concentration of the unreacted sorbent in the fly ash mixture may be too dilute for effective direct recycling. Analyses of the fly ash samples from the economizer, mechanical collector, and electrostatic precipitator hoppers might reveal a possible source of the most concentrated unreacted sorbent. In addition, the reactivity of recovered dry sorbent may not be equal to that of the fresh limestone feed. The recovered sorbent might be deadburned when reinjected into the furnace, while CaO formed from calcination of limestone is not because of particle quenching during the endothermic reaction. Slaking of collected fly ash can hydrate the recovered sorbent and might increase its reactivity. However, water required for slaking has a significant thermal effect on the boiler efficiency and may affect performance of the fly ash collection system.

The feasibility of recycling recovered sorbent has not been thoroughly demonstrated. Reinjection of treated and untreated recovered sorbent has been tried with moderate success by the Central Research Institute of Electric Power Industries of Japan.[1] In one pilot boiler test the recovered lime/fly ash mixture was slaked and injected into the furnace. The recycled hydrated sorbent showed reactivity equal to that of the fresh, dry limestone feed. However, direct recycling of recovered dry sorbent showed greatly reduced reactivity. In addition, investigation into a process to recover sorbent from the sulfate reaction product has been reported, but not developed.[2] The process thermally decomposes the collected calcium sulfate for generation of sulfuric acid and recovers CaO as a byproduct.

MATERIALS HANDLING

The limestone handling system consists of three or four stages: receiving, storage, transfer, and crushing if oversized limestone is received. The design of the system depends on the limestone particle size, bulk density, and the quantity of limestone to be handled. Raw limestone can be purchased either ground or in crushed (lump) form. This section discusses only the handling of crushed limestone. The handling of purchased ground limestone is discussed in Section 7 (see Other Alternatives).

Limestone Receiving

Receiving includes unloading the limestone shipment and transferring to either a long term storage pile or directly to a receiving hopper or storage bin. The receiving equipment can vary depending on the mode of shipment. Typical deliveries by truck are limited to load capacities of about 23 Mg (megagrams) (25 tons) each. Limestone shipments requiring more than about 10 trucks per day (i.e., 230 Mg) at a boiler site would probably be too cumbersome. Larger shipments could be delivered by trains with railroad car capacities ranging from 45 to 91 Mg (50 to 100 tons) per car. For boiler locations with access to navigable waters, very large limestone shipments can be delivered by barge or ships. From the limestone injection rates presented in Table 6-1, it can be seen that boilers rated larger than about 100 MWe power output (regardless of coal type) would need to handle limestone quantities large enough to require shipments by trains or barges.

A schematic of a crushed limestone handling system with railroad car unloading facilities is presented in Figure 6-2. The receiving equipment includes a railcar shaker and puller, unloading hopper and feeder, unloading belt conveyor, a stocking-out belt conveyor, and a sump pump for removal of accumulated water from rainfall, run off, and washdowns in the unloading pit. Unloading the limestone should be accomplished as rapidly as possible to avoid demurrage charges and to minimize associated labor costs. A typical railcar unloading design rate is about 227 Mg (250 tons) per hour. The limestone handling equipment require electrical energy for operating the drive motors. Table 6-2 lists the limestone receiving equipment shown in Figure 6-2 and gives nominal drive motor power requirements. A subtotal power requirement is also shown as a factored equivalent to a limestone feedrate of 12 Mg/hr (13 tons/hr) which approximately corresponds to firing Montana subbituminous coals in a 250 MWe boiler or Illinois bituminous coal in a 100 MWe boiler (see Table 6-1).

Storage

An area for a 30-day limestone stockpile would be desirable for boilers rated larger than 100 MWe power output. For smaller boilers, routine limestone truck shipments might avoid the necessity for a stockpile and the received material could be transferred directly to a storage bin. The equipment required for stocking-out limestone includes a belt conveyor for distribution, a tripper for moveable discharge, and a dust collection system (hood, bag filter, and exhaust fan). The storage equipment shown in Figure 6-2 are listed in Table 6-2.

Transfer

Limestone is transferred from storage to multiple feed bins using belt conveyors and a bucket elevator. A sump pump is required in the pit beneath the storage pile. In addition, a dust collection system is needed for the vents from the covered bins. The total bin capacity should be sized to hold about 24 hours of limestone. The transfer equipment and nominal operating power requirements are shown in Table 6-2.

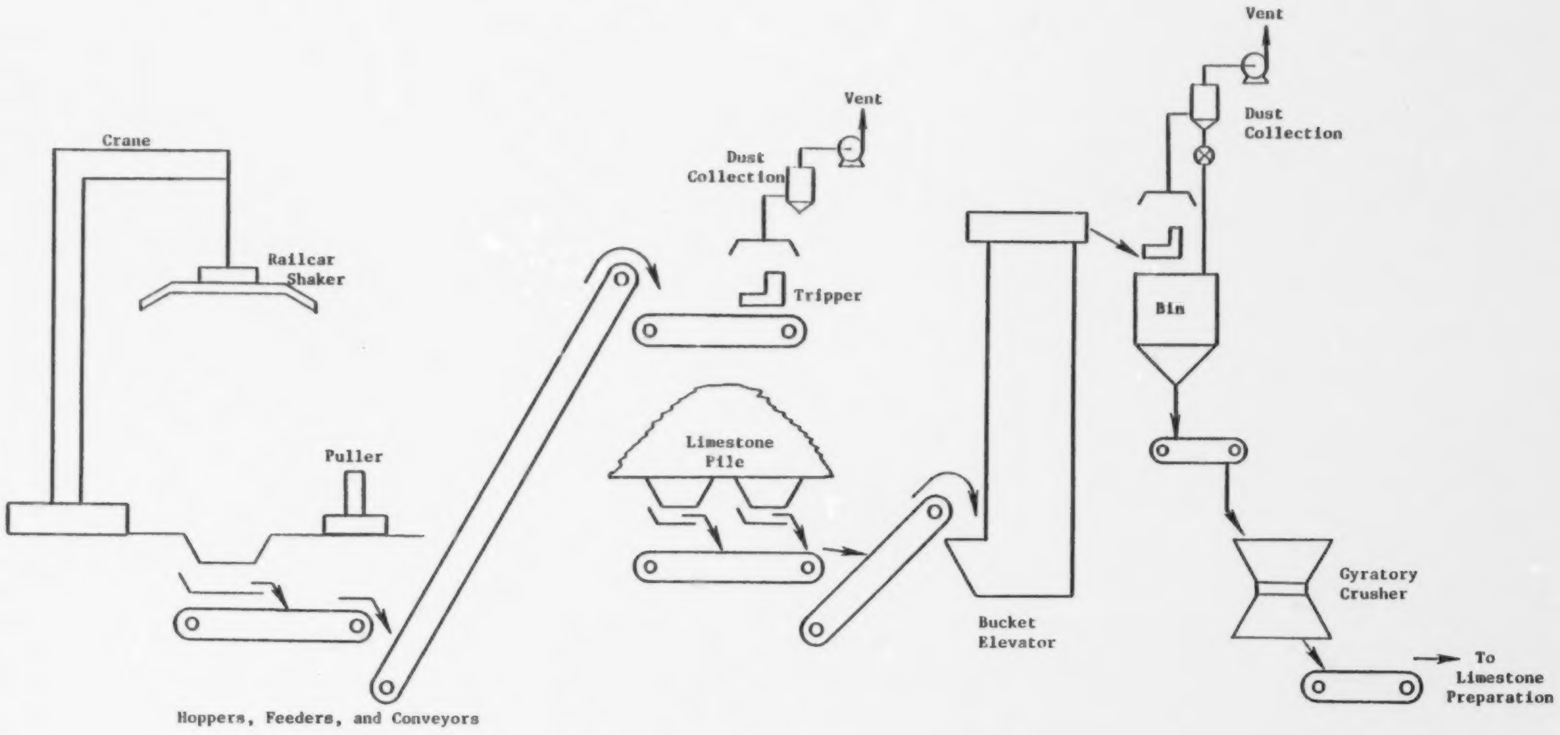
Crane
Railcar Shaker
Puller
Hoppers, Feeders, and Conveyors
Dust Collection
Vent
Tripper
Limestone Pile
Bucket Elevator
Vent
Dust Collection
Bin
Gyratory Crusher
To Limestone Preparation

Figure 6-2. Typical crushed limestone railcar unloading and handling system.

TABLE 6-2. CRUSHED LIMESTONE HANDLING SYSTEM EQUIPMENT LIST

Item	Capacity[d]	Drive Motor,[e] kW
Receiving[a]		
Car Shaker	-	-
Car Puller	91 Mg (100 tons)	19 Pull 4 Return
Unloading Hopper	-	-
Unloading Feeder	227 Mg/hr (250 tons/hr)	2
Unloading Belt Conveyor, 61 m (200 ft) long	227 Mg/hr (250 tons/hr)	4
Stocking-out Belt Conveyor (inclined), 95 m (310 ft) long	227 Mg/hr (250 tons/hr)	37
Sump Pump	227 lpm (60 gpm)	4
Subtotal Equivalent	12 Mg (13 tons)/hr	25
Storage[a]		
Stocking Belt Conveyor, 61 m (200 ft) long	227 Mg/hr (250 tons/hr)	4
Tripper	-	1
Dust Collection System	3740 m^3/hr (2200 CFM)	6
Limestone Pile	30 days	-
Subtotal Equivalent	12 Mg (13 tons)/hr	6
Transfer[a,b]		
Feeders	91 Mg/hr (100 tons/hr)	5
Belt Conveyor, 61 m (200 ft) long	91 Mg/hr (100 tons/hr)	4
Belt Conveyor (inclined), 58 m (190 ft) long	91 Mg/hr (100 tons/hr)	30
Sump Pump	227 lpm (60 gpm)	4
Bucket Elevator, 27 m (90 ft) lift	91 Mg/hr (100 tons/hr)	19
Bin Belt Conveyor, 18 m (60 ft) long	91 Mg/hr (100 tons/hr)	1
Tripper	-	1
Dust Collection System	3740 m^3/hr (2200 CFM)	6
Limestone Bins (covered)	24 hours	-
Subtotal Equivalent	12 Mg (13 tons)/hr	10
Crushing[c]		
Belt Feeder, 3 m (10 ft) long	12 Mg/hr (13 tons/hr)	0.5
Gyratory Crusher, 3.8 to 1.9 cm (1½ to 3/4 in) particle size	12 Mg/hr (13 tons/hr)	56.0
Belt Conveyor, 3 m (10 ft) long	12 Mg/hr (13 tons/hr)	0.5
Subtotal Equivalent	12 Mg (13 tons)/hr	57
Total Equivalent	12 Mg (13 tons)/hr	98

[a] Reference 27.

[b] Reference 28.

[c] Reference 6.

[d] Equipment capacities shown are typical design values.

[e] Individual equipment power requirements are based on the design capacities shown. Subtotals are factored equivalents to a 12 Mg/hr (13 tons/hr) limestone feed rate. The total is simply the sum of the subtotal values. This feedrate approximately represents the requirements of a 250 MWe boiler firing a 0.6% sulfur coal (Ca/S=4) or a 100 MWe boiler firing a 4.0% sulfur coal (Ca/S=2) (see Table 6-1).

Crushing

The requirement for limestone crushing facilities at the boiler site depends on the size of the purchased material. Crushed limestone can be purchased with a range of particle sizes from about 0.6 to 12.7 centimeters (1/4 to 5 inches).[3,4,5] Primary crushers at the quarry site include jaw and gyratory crushers and impact breakers, producing 3.8 to 12.7 centimeters (1.5 to 5 inch) material. Hammer mills and gyratory crushers are used as secondary crushers to reduce the particle size to about 0.6 centimeter (1/4 inch). Most grinding equipment accept feed up to 3.8 to 5.1 centimeters (1.5 to 2 inches) size. However, 1.9 to 3.2 centimeters (3/4 to 1.25 inch) is a more typical design feed size. Therefore, crushing facilities should be included if the limestone supplier cannot guarantee shipment of particle size smaller than 3.8 centimeters (1.5 inches).

The equipment shown in Figure 6-2 include a variable speed belt feeder(s), a gyratory crusher(s), and a discharge belt conveyor. The raw limestone from the in(s) is conveyed and metered by the volumetric feeder(s) to the crusher(s). The final crushed limestone is then directed to the preparation area for grinding.

The operating power requirements for crushing a nominal 12 Mg (13 tons) per hour limestone feed rate are shown in Table 6-2.[6] The total power demand for the crusher is a function of the crushing efficiency and the equipment mechanical efficiency. The work index and Bond crushing law are useful for estimating the power requirements of commercial crushers.[7,8] The work index W_i is defined as the gross energy in kilowatt-hours per ton of feed needed to reduce very large feed to such a size that 80 percent of the product is less than 3.8 centimeters (3/4 inch). Typical crushing work indices for calcium limestones have been reported in the range of 10.2 to 12.7. These values are 75 percent of the dry grinding indices presented in Table 5-3.

The following expression relates power requirements to the Bond work index:

$$P \propto T * \left[\frac{W_i}{C^{0.5}} - \frac{W_i}{F^{0.5}} \right] \qquad (6\text{-}4)$$

where,

P = power required, kW (or HP)
T = feed rate, Mg/hr (or tons/hr)
W_i = work index for limestone
C = crushed product size, cm (or inches)
F = feed material size, cm (or inches)

This energy law is not accurate for directly calculating crushing energy requirements in the absence of operating data. However, the relationship is useful for ratioing power requirements from known operating conditions to other conditions.

LIMESTONE PREPARATION

To maximize limestone utilization in the boiler, limestone preparation requires reducing the crushed stone to a fine particle size, as discussed in Section 5. The equipment required for limestone preparation depends on the grinding method and the preparation route. Extremely fine grinding sometimes requires wet grinding or the use of grinding additives. Wet grinding normally is more expensive overall because of the cost of evaporating the added moisture. Dry grinding is, therefore, the only method considered in this report.

The major limestone preparation equipment item is of course the grinding mill. A variety of grinders such as standard coal pulverizers and ultrafine grinders are available to achieve the desired range of particle sizes. Dry grinding to fine particle size is more efficient if stone moisture content is less than one percent. Since raw limestone moisture content varies widely as discussed in Section 5, thorough drying must be an integral part of the limestone preparation system.

High efficiency in fine particle preparation requires closed circuit grinding with good material circulation and product size control. It is not feasible to grind all the limestone to the desired fineness in a single passage through the grinding elements. Particles must be continuously removed from the grinding chamber and circulated through a classifier. Limestone pulverized to the proper fineness leaves the top of the classifier and oversize particles are separated and returned to the grinding zone.

Grinding mill design, sizing, and operation in limestone service are similar to that for coal preparation. The energy and maintenance requirements might be higher, however, because of the limestone physical properties. Further discussion of the limestone preparation system is presented by the following categories:

- Grinding Mill Types,
- Air Supply Systems,
- Grinding Mill Sizing,
- Limestone Preparation Energy Requirements,
- Equipment Maintenance, and
- Influence of Coal Preparation System.

Grinding Mill Types

The grinding mills available for limestone preparation are categorized by operating speed: high, medium, and slow.[9,10,11,12] Ultrafine particle sizes of 1/2 to 10 micrometers (μ) can be achieved with fluid-energy or jet mills. However, mill manufacturers do not recommend these ultrafine grinders for limestone service since the physical properties of limestone are not suitable.[13]

High Speed--

High speed grinding mills operate at rotational speeds greater than 225 RPM. The simplest pulverizer is the high speed hammer mill or impact mill. There are two classes of these mills for producing fine and ultrafine particles. Particles slightly finer than 200 mesh (74μ) can be produced in a machine with a series of swing hammers mounted on a shaft. A fan is usually mounted on the shaft to provide air flow to carry the particles through some form of classifier. These pulverizers generally have the lowest first cost, and are relatively simple to maintain. However, they do require much maintenance. The feed should be a relatively soft nonabrasive material with a hardness of 1.5 or less (MohS scale). Hammer mills can accept feed up to 3.8 centimeters (1½ inch) size, but 1.9 centimeter (3/4 inch) material works best. To prepare limestone to particles averaging 1 to 20μ size, with substantially all particles passing a standard 325-mesh screen (44 μ), an ultrafine hammer mill can be employed.

Medium Speed--

Medium speed mills operate between 75 and 225 RPM. These pulverizers are the most widely used types for coal preparation. There are two general grinding element designs: the ball-and-race and the roller-ring types. In the ball-and-race design, there is a series of balls located between two races. The lower race is driven causing the balls to rotate. The upper race is usually spring loaded, the springs providing the force for grinding. The roller-ring design has two configurations: (1) where the ring is stationary and the rolls rotate, and (2) where the rolls are mounted off the mill housing and the ring rotates. The second configuration is referred to as a bowl mill. Grinding force is applied via springs or hydraulic pressure.

The principle of operation of both designs is basically the same. Both are vertical-drive designs utilizing internal air circulation with an integral, stationary cyclonic classifier for product particle size control. Crushed material is fed by gravity to the center of the grinding zone where it mixes with partially ground material. Centrifugal force carries the material outward under the grinding elements. A high velocity hot air stream sweeps up the ground material at the perimeter of the grinding zone and moves it up to the classifier. As the air stream moves through the mill housing, some of the larger or more dense particles (aerodynamically heavier) fall out and back into the grinding zone. The fine particles pass out the top of the classifier with the air stream. The heavier particles from the classifier drop down to the grinding zone. If the air flow through the mill fluctuates, classifier vane openings can be adjusted to maintain the pressure drop required for a constant particle size product.[14,15] Any heavy, hard-to-grind particles pass through to the perimeter grinding zone and fall through the air stream to the bottom of the pulverizer housing. In coal preparation, such hard materials are rejected out through a bottom port of the mill housing called the "pyrites trap".

Medium speed pulverizers are commercially used to produce a wide range of particle sizes. In pulverized coal preparation, the rank of coal and its end use govern the fineness to which coal must be ground. Coal fineness specifications range from 60 (low rank coals) to 75 (low volatile bituminous) percent through 200 mesh (74 μ). For limestone grinding, particle size as fine as 99.5 percent through 325 mesh (44 μ) can be achieved, but at greatly reduced capacity.[16,17]

Medium speed pulverizers are somewhat higher in initial cost than high speed mills. However, they will operate for much longer times between maintenance periods. They will also maintain quality of product essentially over the entire operating period. For continuous grinding service, manufacturers of roll-and-race and bowl mills stress that it is important to provide a spare pulverizer. This way, a mill can be out of service for maintenance without impairing grinding capacity.

Slow Speed—

Slow speed mills operate below 75 RPM and are offered in four designs: Ball-and-race, roll-and-race, roller, and ball mills.

In the roll-and-race design, three equally spaced, contoured grinding roll wheels (sometimes called "tires") are mounted on a central vertical pivoting assembly. A race rotates at only 21 to 29 RPM below the rolls. The slow speed results in quiet and smooth operation. The mill is air-swept with an internal classifier and operates similar to the medium speed mills.

A slow speed roller type mill, similar in construction and operation to the medium speed bowl mill, is the saucer mill.[18] The difference is that the saucer mill's grinding ring is a flat disc. This mill is subject to loss of capacity as wear progresses on the clearance between the roller and race.

Ball mills are the oldest proven methods for grinding limestone, coal, and many other materials. Well designed ball mills generally are very reliable, operating continuously for a year or longer before major maintenance is required. These pulverizers are essentially slow turning horizontal cylinders filled with steel balls. Cascading balls pulverize the material within the rotating drum. The term pebble mill is used when spheres of flint, porcelain, or zircon are employed. Small ball mills can be designed with an air-sweep for drying. The mill may be fitted with integral fixed classifiers or external in-line classifiers. A problem with ball mills in dry limestone service is that the ball may become coated thereby reducing their pulverizing effectiveness. This factor must be incorporated in ball mill design. The capital cost differential between ball and vertical-spindle-mill grinding systems is small. Space requirements for ball mills are quite high because soundproof housing is required. For any given capacity, the ball mill is larger in size and heavier in construction than high- or medium-speed pulverizers.

When the mill's length is greater than its diameter, it is called a tube mill. Some tube mills have tapered or conical drums with internal sections of various size balls. Large balls are used in the feed section; progressively smaller balls are used to grind the material to finer and finer size until the desired product is achieved at the outlet. The stone feed to tube mills must be dry because air-sweeping through the mill is not very efficient. Thus, for high moisture limestone, a separate feed air-drying system is required. In addition, an external pneumatic conveying system and classifier must be employed to carry away and separate the discharged mill product.

Ball mills are capable of grinding very abrasive materials to very fine particle size. Product fineness up to 80 percent through 400 mesh (37 μ) is achievable. One limestone product with a particle size distribution of 90 percent through 350 mesh (40 μ), 55 percent through 10μ, and 10 percent through 2.5μ is commercially produced.[19]

Air Supply Systems

Proper air flow to the pulverizer is required to dry moist feed material, circulate and classify the pulverized material, and convey the product out of the mill. Air-swept pulverizers have a minimum air flow requirement, to prevent settling of the particles at various pulverizer loadings. At reduced boiler loadings, the primary air flow through coal pulverizers and the burners is usually decreased linearly, but not in direct proportion to the reduction in coal firing rate. A minimum of 70 percent of design air flow is required at 50 percent boiler load.[20,21] Three air supply systems can be employed: suction, pressurized, and external. The external system is only required with tube mills, as previously discussed.

Suction System--

Hot air from an external air heater is induced through the pulverizer by an exhauster fan on the discharge of the mill. The pulverizer operates under a slight suction, is generally cleaner, and does not require a separate sealing air system. The fan operates at a relatively low, constant temperature; therefore, power consumption is comparatively low. However, the exhauster must handle the pulverized material resulting in high maintenance requirements.

Pressurized System--

Hot air is forced through and pressurizes the pulverizer in this design. The air fan can be located on the inlet side of the mill and draw cold air through an external air heater. The fan must operate at the highest temperature envisioned and thus, the power requirement is the highest. The fan could also be located to operate on cold air and force the air through the heater first, then the mill. In either case, the fan handles only air and is not subject to the pulverized material. In all pressurized operations, a sealing air system must be provided to prevent dust emissions to the atmosphere and to seal internal mechanical parts. Since the late 1960s, the majority of air supply systems for coal pulverizers have been of the pressurized design.

Grinding Mill Sizing

There are three main factors which affect the operating capacity of pulverizers: the grindability of the limestone, the desired fineness of the product, and the moisture content. Coal pulverizers are typically rated by manufacturers at a reference Hardgrove Grindability Index (HGI) of 50 and a particle fineness of 70 percent through 200 mesh (74μ). Each manufacturer has its own factors for adjusting capacity according to grindability. In general, capacity is affected by 10 to 20 percent for each ten point change in grindability. The effect of grindability is shown in a general capacity factor graph presented in Figure 6-3.

The effect of product particle size is also shown in Figure 6-3. For grinding to 75 percent through 200 mesh (74μ), mill capacity is affected by about 1.5 percent for each one percentage point change in particle fineness. In comparison, mill capacity is reduced by about 70 percent if a finer limestone particle size of 99.5 percent through 325 mesh (44μ) is desired.

In order to pulverize limestone properly, essentially all surface moisture must be removed. As discussed in Section 5 the grindability of lower rank coals is dramatically and unpredictably affected by moisture content. A similar effect may occur with limestones. The air heater for materials drying in the pulverizer must be designed for the highest moisture content expected for the range of limestones handled. Moistures in excess of those for which drying capability is available will cause an appreciable reduction in pulverizer output.

The available capacities of various pulverizer types is presented in Table 6-3. Each of the three operating speed mill categories previously discussed is represented. The mill sizes range from less than one Mg (1.1 tons) to 91 Mg (100 tons) per hour.

Limestone Preparation Energy Requirements

Grinding of limestone to fine particle size requires electrical energy for driving the pulverizer and for operating the associated fan for the air supply system. To minimize boiler upsets, the total combustion air to the furnace should remain the same with limestone injection. However, net electrical power requirements for air handling will be higher if some of the low pressure combustion air is directed through a pulverizer system for limestone preparation and injection. Thermal energy is also required to provide hot air for drying moist limestones to less than one percent water content. These thermal requirements are addressed in Section 9.

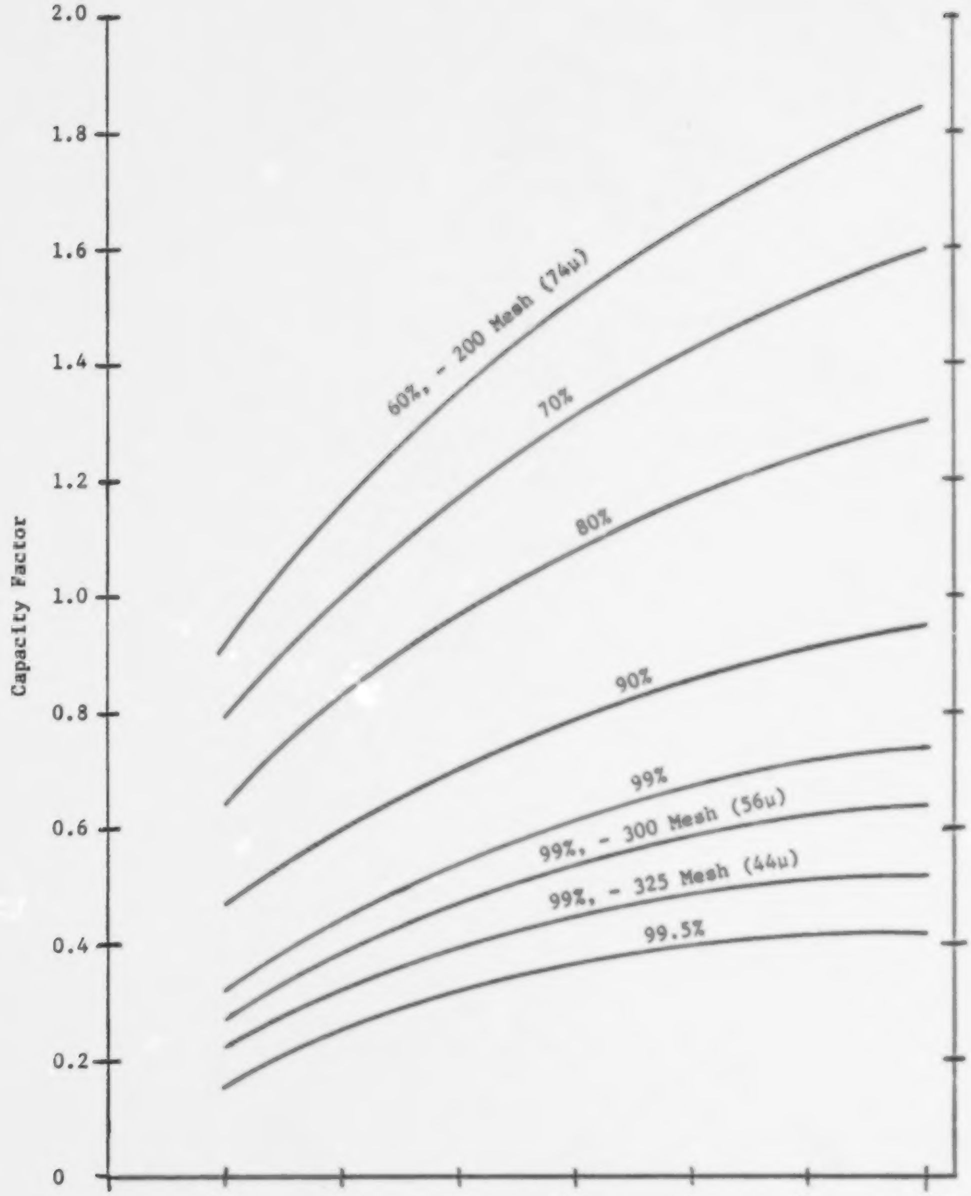

Figure 6-3. Effect of grindability and fineness on pulverizer capacity.[a]

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[a] Reference 12 and 17.

TABLE 6-3. PULVERIZER CAPACITY RATINGS

Mill Type	Available Size Ranges Mg/hr	 (tons/hr)
Hammer Mills[a]		
Fine Product	0.1 - 14	(0.1 - 15)
Ultrafine Product	0.9 - 1.8	(1 - 2)
Ball-and-Race Mills[b]	1.3 - 18	(1.5 - 20)
Roll-and-Race Mills[b]	18 - 95	(20 - 105)
Bowl Mills[c]	0.9 - 91	(1 - 100)
Ball Mills[a,d]	0.1 - 45	(0.1 - 50)

[a] Reference 11.

[b] Reference 12.

[c] Reference 29.

[d] Reference 9.

Electrical Energy--

The power required for dry grinding of limestone depends on the quantity and particle size of the feed, the particle size of the product, and the properties of the limestone. The semitheoretical Bond crushing law discussed previously can be used with a dry grinding work index to ratio the power demand for various conditions. Dry grinding work indices for limestone are presented in Section 5, Table 5-3.

In actual practice, the total power required for dry limestone grinding is somewhat different for each type of grinding mill. The power input for ball mills typically is about 50 percent higher than for other pulverizer types. The power demand for ball mills is essentially constant, regardless of grinding load, because of the energy required for rotating the cylinder and the balls. Table 6-4 shows some typical limestone grinding power requirements. The operating data show that power requirements increase by a factor of three when particle fineness increases from 75 percent through 200 mesh to 99.5 percent through 325 mesh.

A new lower energy grinding technique called "ultrasonic grinding" is under study by the U. S. Department of Energy.[22] Laboratory test results have shown that for material with an HGI of 56, particle fineness of 90 precent through 325 mesh (44μ) with 37 percent below 7μ is achievable using only 41 kWh/Mg (37 kWh/ton). This compares very favorably to conventional grinding, which would require about 360 kwh/Mg (330 kWh/ton).

The power required for supplying air to the limestone pulverizer depends on the location of the fan, as previously discussed. Power consumption of the pulverizer fan is an important item in the operating cost of coal and limestone preparation. The fan power requirements can be described by the following compressible flow relationship:

$$P_f \propto W * \left[\frac{\Delta P}{D} + V^2 \right] \qquad (6\text{-}5)$$

where,

P_f = Power required for fan, kW (HP)
W = Total mass flow rate of air and solids mixture thru fan, Mg (tons) per hour
P = Differential pressure across fan, kPa (in. water)
D = Average density of air and solids mixture thru fan, kg/m^3 (lbs/ft^3)
V = Velocity at fan discharge m/sec (ft/sec)

The flow of air required for conveying and classifying the pulverized product from the grinding zone varies with the size of the grinding mill and the particle specific gravity. The required weight ratio of sweeping-air to solids handled for pulverized coal is about 1.2 to 2.0. The density of limestone particles vary widely, but in general, limestone

TABLE 6-4. ELECTRICAL POWER REQUIRED FOR GRINDING CRUSHED LIMESTONE

Pulverizer Type	Product Fineness		Relative Capacity Factor	Grindability Index, HGI	Operating Power	
	%, -	Mesh Size (μ)			$\frac{kWh}{Mg}$	$\frac{kWh}{ton}$
Medium-Speed[a] Air-Swept Mill	75,	200 (74)	1.0	NA	17	(15)
	75-78,	200 (74)	-	60-70	19	(17)
	85,	200 (74)	0.82	NA	17	(15)
	95,	200 (74)	0.64	NA	24	(22)
	99,	200 (74)	0.50	NA	29	(26)
	99,	300 (50)	0.43	NA	34	(31)
	99,	325 (44)	0.36	NA	41	(37)
	99.5,	325 (44)	0.29	NA	49	(45)
Ball Mill[b]	82,	200 (74)	1.0	40[c]	25	(23)
	70,	325 (44)	1.70	50	19	(17)
	95,	325 (44)	0.75	50	41	(37)
	mean @ 7μ		-	40[c]	360	(330)

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[a] Reference 17 and 30

[b] Reference 31 and 32

[c] Approximate - not measured

NA - Not available

has about twice the density of coal. Thus, in limestone service, the air to solids ratio would be about 2.0 to 2.5 for the same particle fineness as required for pulverized coal.[23]

The differential pressure required by the fan is a function of the pressure drop through the air heater, the grinding mill, and the pneumatic conveying lines. Pressure drop through the air heater is typically about only 0.7 kPa (3 in. water). Grinding mills with internal classifiers are typically controlled at 2.5 kPa (10 in. water) pressure drop. A typical differential pressure for a coal pulverizer air supply fan is about 7.7 kPa (31 in. water).[24] In comparison, the forced draft (F.D.) fan supplying the remaining combustion air to the furnace typically has a differential pressure of only 2.2 kPa (9 in. water). Thus, any air diverted from the F.D. fan to the limestone pulverizer air supply fan will cause increased electrical power requirements.

The average density of the air and solids mixture handled by the fan depends on the temperature and solids loading. At higher temperatures, the air density is lower causing the required fan power to be higher for an equivalent air mass. For equivalent fan differential pressures, exhauster power consumption is usually about 15 percent more than clean-air fan power because of separation of solids on fan blades and direct acceleration of the solid particles.

Estimates of air fan power requirements are included in the analysis of each limestone injection alternative discussed in Section 7.

Thermal Energy--

The thermal energy required for dry grinding depends on the moisture content of the crushed limestone. The amount of thermal energy needed is determined by the sum of:

- the sensible heat to raise the air temperature from ambient to that required for thorough limestone drying,
- the sensible heat to raise the temperature of the limestone, and
- the sensible and latent heat required to evaporate the water from the limestone.

The required air supply temperature to the grinding mill varies from about 200°C (400°F) for low moisture limestones to over 315°C (600°F) when high moisture levels are encountered. The heat source can be the boiler air preheater or a separate hot air supply heat exchanger. Waste, low pressure steam could possibly be utilized to provide part of this heat requirement but not as the only heat source since its temperature is lower than the required air temperature.

Equipment Maintenance

For limestone preparation, maintenance would be required on the pulverizer and the air fan. Pulverizer maintenance is a major concern with all operators. Maintenance will vary with the mill design, the product particle size, the limestone grindability and abrasion (hardness), and any hard, foreign material mixed with the limestone. Mill wear is sometimes excessive on the high-speed pulverizers. Medium-speed pulverizers operate for much longer periods between maintenance requirements. However, for the continuous demand in coal preparation service, a spare mill is always installed. Ball mills, on the other hand, reportedly have an availability record that is unmatched by any other pulverizer. Spare ball mills would not be required. Initial maintenance on ball mills requires only periodic replacement of the balls, which is relatively simple and can be done while the mill is in service.

The maintenance of all pulverizer types increases as the product particle fineness is increased. In addition, limestones with lower HGI would cause more maintenance. The property data presented in Section 5 indicate that limestone, in general, tends to be harder and more abrasive than most coals. Thus, pulverizer maintenance from abrasion may increase for limestone service compared with that for coal.

The maintenance requirements for the air supply fan depend on where the fan is located relative to the mill. An exhauster fan located on the mill outlet would obviously incur more maintenance because of solids wear.

Influence of Coal Preparation System

The limestone preparation route may partially or totally interface with coal preparation or may be completely separate. There are two principal systems used for coal preparation: the direct (or unit) system and the indirect (or bin) system. The direct preparation system is almost exclusively used for new pulverized coal boiler installations.[25] The direct route is less complicated, requires less ancillary equipment, and has lower operating costs. However, some new bin preparation systems are still being installed at the customer's request.[26]

Direct System--

Direct coal preparation permits continuous utilization of raw coal from the bunkers. The coal is directed by gravity down through a volumetric or gravimetric belt feeder to an air-swept pulverizer and then pneumatically conveyed directly to the boiler furnace in a single continuous operation. The pulverizer air supply is drawn or forced through an air preheater in the convection section of the boiler. This boiler air supply is called primary air.

The influence of limestone injection on a direct coal preparation system depends on the condition of the limestone and whether the sorbent is mixed with the raw coal or with the pulverized coal/primary air mixture after the coal pulverizer. Several alternative coal/limestone direct injection schemes are discussed in Section 7.

Indirect System--

The bin system of coal preparation is not widely used for new installations, but several remain in operation. This system was required when pulverizing equipment could not be relied upon for uninterrupted operation. In this system, the coal is pulverized at a central grinding station, pneumatically conveyed to a storage bin, and separated from the hot, moisture laden air. The prepared coal is then pneumatically conveyed from the storage bin by a differential-pitch screw pump through long transfer lines to several feed bins above the boiler.

Since a bin preparation system is not tied directly to the firing of the boiler, it will provide more flexibility for interfacing with limestone preparation. The remote location would avoid any potential space limitations near the boiler for limestone preparation. Analysis of remote coal/limestone preparation and injection alternatives are discussed in Section 7.

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SECTION 7

ALTERNATIVE LIMESTONE INJECTION SCHEMES

There are several schemes that can be used to prepare the limestone and inject it into the boiler furnace. These include preparation of the limestone together with the coal or separately and injection of the limestone with the primary air through the coal burner, with the secondary or tertiary air around the burner, or through separate injection nozzles installed at any available location on the furnace walls. Selection of the injection method will be influenced by SO_2 control considerations, limestone and coal properties, and the existing coal feed system design.

In this subsection, four alternative limestone injection schemes (labeled Alternatives A through D) are presented and some variations discussed. For each alternative the operation of the limestone handling/injection system and any interface with the coal firing system are described. Also, the required ancillary equipment and operating energy requirements are described. The advantages and disadvantages of each alternative are discussed. In addition any documented historical experience with each alternative is discussed. Boiler impacts, such as slagging and fouling associated with application of LIMB are discussed in Section 9.

ALTERNATIVE A: BURNER INJECTION OF CRUSHED LIMESTONE PASSED THROUGH COAL PULVERIZERS

The simplest, most straightforward injection scheme is to mix crushed limestone with the raw coal. The limestone and coal are pulverized together in the coal preparation system with the mix conveyed by the primary air through the burners. When materials with different grindabilities are pulverized together, the grinding elements are designed for the hardest material. The material with the higher HGI will probably be pulverized to a finer size.[1] This injection scheme can be used with either the direct or bin coal preparation system. An example of this injection scheme with a direct fired coal preparation system is shown in Figure 7-1.

The only required ancillary equipment is for transfer, storage, and feeding the crushed stone. A continuous bucket elevator is required to lift the limestone from the crusher discharge to the silo. In addition, a dust collection system is needed for the vent from the covered silo. A gravimetric weigh belt feeder could be used to meter the limestone directly to the grinding mill, in the same fashion as the coal.

In many cases, the limestone could be stored in the coal bunker rather than a separate silo by partitioning the bunker to allow a special section for limestone. This limestone storage would require

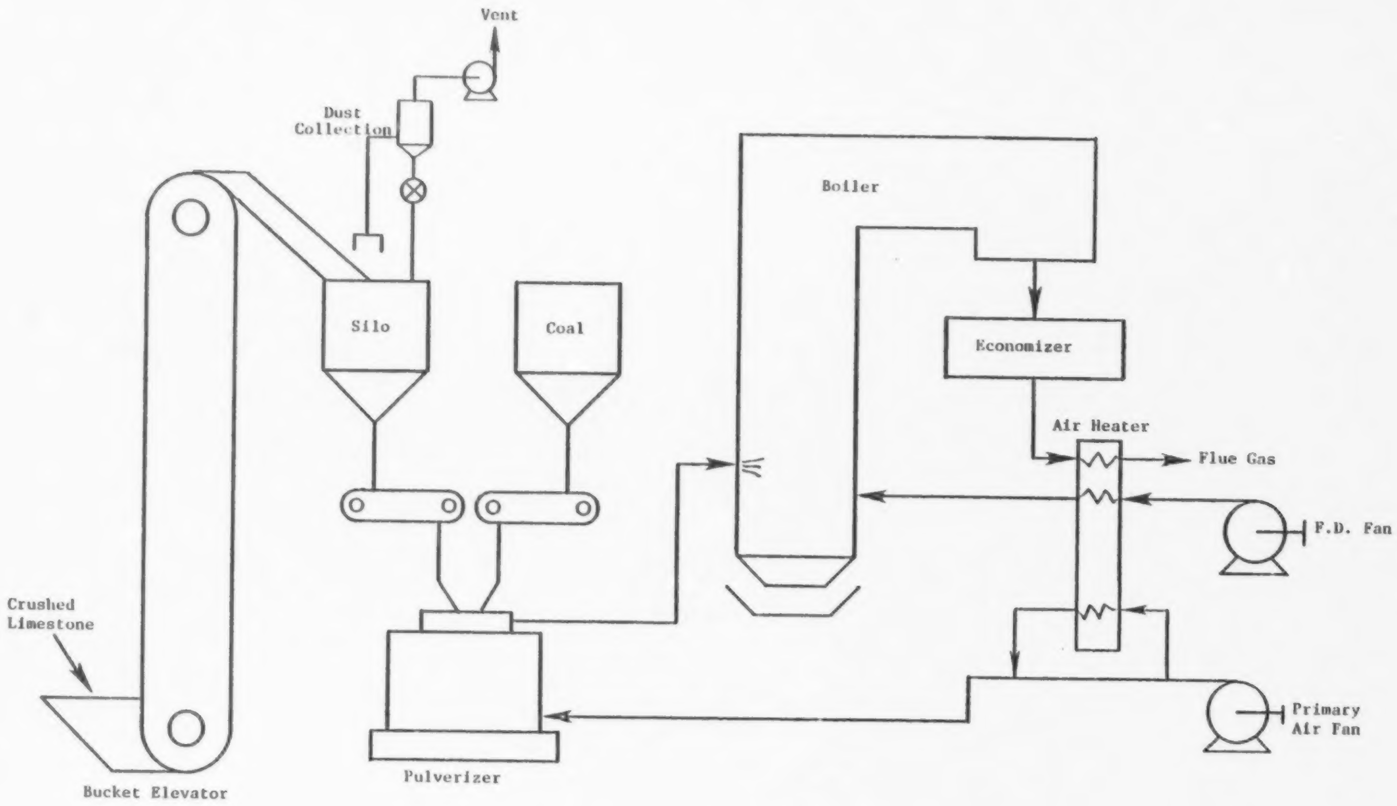
Vent
Dust Collection
Boiler
Silo
Coal
Economizer
Air Heater
Flue Gas
F.D. Fan
Crushed Limestone
Primary Air Fan
Pulverizer
Bucket Elevator

Figure 7-1. Alternative A: Burner injection of crushed limestone passed through coal pulverizers.

about 8 to 30 percent of the total bunker capacity, depending on the limestone injection rate, as discussed in Section 6. Also, the limestone and raw coal could be mixed in the coal bunker after being separately metered on weigh-belt conveyors. However, mixed storage of the two materials would present a slight lag time in responding to a desired change in the limestone injection rate. The limestone preparation system could be immediately adjusted, but the boiler would not be affected until the original limestone/coal mix was emptied from the bunker. The system response time would be about one day since coal bunkers are typically sized for about 30 hours operating capacity.[2] In addition, a non-uniform feed of the limestone/coal mix could cause problems with this second option if the crushed limestone became segregated from the raw coal in the bunker. Flame stability problems and/or decreased SO_x control could result if slugs of limestone were injected through the burner.

The electrical power requirements for a nominal 12 Mg (13 tons) per hour limestone feed rate with this preparation and injection method are presented in Table 7-1. To compare operating impacts with other alternatives, it is assumed that the coal firing rate remains constant. The pulverizer is assumed to have sufficient extra capacity to handle the limestone grinding load. The primary air flow through the pulverizer and burners is increased at an air-to-limestone mass ratio factor of about 2:1 to convey the limestone. The total combustion air to the boiler is expected to remain constant. However, there will be a net increase in total energy requirements for diverting air from the forced draft (F.D.) fan to the primary air fan because of the difference in fan pressures by about 5.5 kPa (22 in. water), as discussed in Section 6.

Advantages of Alternative A

There are two main advantages of this injection scheme over other alternatives. First, if the coal preparation system has excess capacity, a minimum capital investment is required for sulfur oxide emission control. Separate limestone grinding and pneumatic injection equipment are not required. This may be an overriding factor for retrofit of boilers in old power plants where space limitations might present problems for installation of additional equipment. The second advantage is the potential for intimate mixing of the limestone and coal particles in the pulverizer. Close contact between the limestone and coal may be important in optimizing sulfur oxide removal efficiency.

Disadvantages of Alternative A

This injection scheme has several potential disadvantages. However, certain coal preparation designs, similar limestone and coal properties, and low limestone injection rates would minimize some or all of the problems. First, if the coal pulverizers have no excess capacity, the coal firing rate would have to be decreased to allow for the limestone

TABLE 7-1. EQUIPMENT LIST AND POWER REQUIREMENTS FOR ALTERNATIVE A

Item	Electrical Power,[a] kW
Bucket Elevator, 23 m (75 ft) lift	2
Limestone Silo	-
Weigh-belt Feeder, Gravimetric	2
Pulverizer, medium-speed, 75% through 200 mesh (74μ)	224 [limestone only]
Primary Air Fan, 2:1 air/limestone mass ratio, ΔP net = 5.5 kPa (22 in. water)	49
Bag Filter and Fan, 3740 m^3/hr (2200 CFM)	6
Total	283

[a] Based on a limestone feed rate of 12 Mg/hr (13 tons/hr). This feedrate approximately represents the requirements of a 250 MWe boiler firing a 0.6% sulfur coal (Ca/S=4) or a 100 MWe boiler firing a 4.0% sulfur coal (Ca/S=2).

grinding load. This would result in a significant derating of the boiler. This derating requirement would probably occur for most boilers, especially where the coal being fired is of lower quality or is harder to grind than the original design coal. As discussed in Section 5, lower quality coal generally has a lower grindability index, lower heating value, and a high moisture content, all contributing to a requirement for more pulverizer capacity. Boilers that are direct fired would naturally need to account for all these factors. On the other hand, boilers fired by the indirect, bin system may have little difficulty handling the extra grinding load of the limestone. This is because the coal pulverizers with bin preparation systems are often designed oversized so that they do not have to run continuously. The extra design capacity allows the preparation system to fill the feed bin with pulverized coal, even while the boiler is firing at full load.

Another disadvantage could occur if the limestone properties are not compatible with those of the coal. Since limestone moisture content can range to 20 percent and higher, the pulverizer drying air systems for the low moisture eastern bituminous coals could be undersized for this limestone injection scheme. Also, injection of limestones with grindability indices lower than that for the coal may significantly decrease pulverizer output and increase power requirements. Again, bituminous coals having less than two percent moisture, for which the HGI typically ranges higher than 80, may present the most problems for limestone/coal compatability. In addition, since the particle specific gravity of limestone is higher than that for most coals, the air flow for sweeping the pulverizer and for conveying the coal/limestone mix to the burners may need to be increased. Insufficient air flow would allow the limestone particles to settle in the pneumatic transfer line to the burner. A significant build-up in these transfer lines can increase pressure drop, cause a reduction in air flow, and lead to further settling out of limestone and coal. Insufficient sweeping air in the vertical-spindle pulverizers could lead to limestone settling-out in the base of the mill housing and piling up in the pyrites trap.

A third disadvantage of grinding limestone with coal is the potential lack of flexibility to control limestone particle size. Optimum sulfur oxide removal efficiency may require a limestone particle size finer than the standard pulverized coal specification. Actually the limestone particle size passing through the pulverizer cyclonic classifier may end up somewhat finer than the coal particle size.[3] This could result from the higher limestone particle density causing increased recirculation of the limestone through the pulverizer. Theoretical aerodynamic analysis of the difference in limestone and coal particle specific gravities indicates that most of the limestone particles discharged from air-swept pulverizers might be as fine as 300 mesh (53μ).

A fourth disadvantage may result because of potential problems with flame stability during limestone injection with coal. The possibility of periodic slugs of limestone was previously mentioned. Even with uniform mixing, high limestone feed rates may cause separation of the coal particles to the extent that a consistent flame is impeded. A stable flame is expected at low limestone injection rates. Past tests have shown no flame problems with limestone or dolomite injection rates slightly higher than the (Ca-Mg/S stoichiometric ratio for coals with up to four percent sulfur content.[4,5,6] However, flame stability problems may occur with coals containing more than four percent sulfur and Ca/S ratios greater than 2.0. In these cases the limestone would represent more than 25 percent of the coal firing rate. Flame stability could also be affected if the primary air flow rate needs to be increased to keep the heavier limestone particles in suspension during pneumatic transport to the burners. An increase in this air flow would tend to move the flame off of or away from the burner.

A fifth disadvantage of injecting limestone with coal is the potential for decreased pulverizer reliability and increased maintenance requirements for the entire coal preparation/firing system. Abrasion from limestone particles may lead to increased wear in pulverizer grinding elements. The exhauster fans for suction operated pulverizers would be especially vulnerable to abrasion. For coal preparation by the bin system, maintenance of the pulverized coal pneumatic transport pump would increase with the limestone/coal mixture. Finally, pneumatic conveying lines, especially at turning points (elbows) and the burners would be subjected to increased erosion. The maintenance impact from limestone injection will depend on the materials of construction used for the coal preparation/firing system and on the limestone injection rate.

A sixth disadvantage is the lack of flexibility in the furnace injection point when limestone is mixed with coal. It may be necessary to inject limestone at other points in the furnace to optimize sulfur oxide removal efficiency.

A final potential disadvantage of injecting limestone with coal is the impact on limestone reactivity. The performance of limestone injection during full-scale tests with conventional burners in the 1960s and 1970s suffered because of low SO_2 removal efficiency caused by "deadburning" of the limestone at high flame temperatures. Unless the multistaged burners can sufficiently decrease flame temperatures to prevent deadburning or the reducing zone sulfur capture reactions occur, limestone injection with coal may not be feasible.

Historical Experience with Alternative A

Mixing of crushed limestone with raw coal for sulfur oxide emission control was tried on a pilot scale and in full-scale operations from the mid-1960s to the mid-1970s in the U. S. Full-scale limestone injection using this technique was tried in pulverized coal boilers by at least three utilities: Wisconsin Electric, Detroit Edison, and Kansas Power and Light companies.

Wisconsin Electric Power Company conducted several days of tests during 1964 on an 80 MW_e boiler.[7] A 2.8 percent sulfur, eastern bituminous coal was fired. Dolomite and coal were conveyed by separate weigh belt feeders to the coal bunker. The mix was pulverized at a Ca-Mg/S ratio of 0.65 to 1.30 to 65 percent less than 200 mesh. Operation of the pulverizers was not affected by the limestone. No flame stability problems were noted.

Detroit Edison conducted 30 days of tests during 1966 and 1967 on a 325 MW_e boiler.[8] The coal being fired contained 3 to 4 percent sulfur and 10 to 14 percent ash. Dolomite was pulverized with coal in the same bowl mill at an injection rate slightly higher than the Ca-Mg/S stoichiometric ratio. No sorbent preparation or injection problems were reported.

Kansas Power and Light Company continuously injected limestone in a 125 MW_e boiler (unit 4) at its Lawrence Station from 1968 to the mid-1970s.[9,10,11] The boiler was fired by a midwestern bituminous coal with about three percent sulfur and 8 to 10 percent ash. Adequate pulverizer capacity was available to carry full boiler load when firing a limestone/coal mixture with the existing burners. Crushed limestone and coal were metered on separate weigh belt conveyors and mixed together in the raw coal bunkers. The limestone injection rate was equal to a Ca/S ratio of 1.0 to 1.5. No excessive segregation (less than five percent) of the coal/limestone mixture occurred in the coal bunker. The pulverizer power requirements for the coal/limestone mixture were unchanged from that required for the same total feed rate of coal alone. A slight increase in wear of the pulverizer grinding elements occurred with the limestone/coal mixture.

ALTERNATIVE B: BURNER INJECTION OF GROUND LIMESTONE PASSED THROUGH COAL PULVERIZERS

With this injection scheme, limestone and coal are prepared in a cascade or tandem arrangement. Crushed limestone is ground separately to the desired particle size and fed to the coal pulverizer for mixing. The pulverized coal/limestone mixture is conveyed by the primary air through the burners. While this injection scheme could be used with either the direct or bin coal preparation system, only the direct system is discussed since the operating impacts are similar with either system.

There are two possible arrangements for utilizing this tandem scheme of limestone injection. If sufficient room is available around the boiler, a limestone grinding mill could be installed next to the coal pulverizer (e.g., within about 3 m (10 ft)). Then, a portion of the hot primary air would be directed to the limestone grinding mill. The primary air would sweep through the grinding mill picking up limestone of the desired particle fineness. It would then be mixed with the rest of the primary air, pass through the coal pulverizer, and convey the coal/limestone mixture to the burner in continuous, uninterrupted flow. The required ancillary equipment for this arrangement would be the same as described for Alternative A, except for the extra pneumatic transfer lines around the grinding mill and pulverizer. Also, an extra primary air fan would be required to overcome the grinding mill pressure drop. This first arrangement of the tandem injection scheme (B_1) is presented in Figure 7-2.

The nominal power requirements for injection arrangement B_1 are presented in Table 7-2. The coal firing rate is assumed to remain constant. Crushed limestone is assumed to be ground to a fineness of 99 percent through 325 mesh (44μ) to achieve higher sorbent utilization than with the standard coal specification for Alternative A. This increases energy requirements as shown in Table 6-4 (Section 6). The primary air fan power requirements are the same as for Alternative A. The grinding mill air fan power requirements are based on a typical mill pressure drop of 2.5 kPa (10 in. water) and an air supply temperature of 315°C (600°F). An additional 1.5 kPa (6 in. water) pressure drop through the pneumatic piping around the mill is estimated from typical pulverized coal conveying requirements. The total energy requirements for this arrangement are about twice that shown in Table 7-1 for Alternative A.

If arrangement B_1 is not feasible, a second, more costly and complex tanden injection arrangement would call for a remote limestone preparation system. The complexity of this second arrangement would depend on its location and the storage and handling facilities for the ground limestone product. The simplest remote arrangement is to install a grinding mill close enough to the boiler area to convey the ground limestone directly from the mill to the raw coal in the bunker. Unfortunately, the elevation to the top of the coal bunker is probably 31 m (100 ft) or more above grade. The capital and operating costs for the required long pneumatic discharge line from the grinding mill may prove to be excessive. In addition, this arrangement may present a segregation problem with the fine limestone particles sifting down through the raw coal. It would probably be better to install a partitioned section in the bunker or install a limestone feed bin next to the coal bunker. Also, many existing boiler sites would not have sufficient space available around the coal bunker for this remote arrangement. Thus, a central limestone grinding system similar to a coal bin preparation system would probably be required and located a good distance from the boiler. A remote, central limestone preparation system with this second tandem arrangement (B_2) is presented in Figure 7-3.

The nominal power requirements for injection arrangement B_2 are presented in Table 7-3. Again, the coal firing rate is assumed to remain constant. The limestone grinding power requirements are equal to those for arrangement B_1. The air supply fan for the grinding mill is assumed to have the same discharge pressure as a primary air fan for direct coal pulverizing. A pneumatic/differential-pitch screw pump is required for transfer of the ground limestone to feed bins near the coal pulverizers. No data on the increase in coal pulverizer power requirements for mixing preground limestone with coal was obtained during this

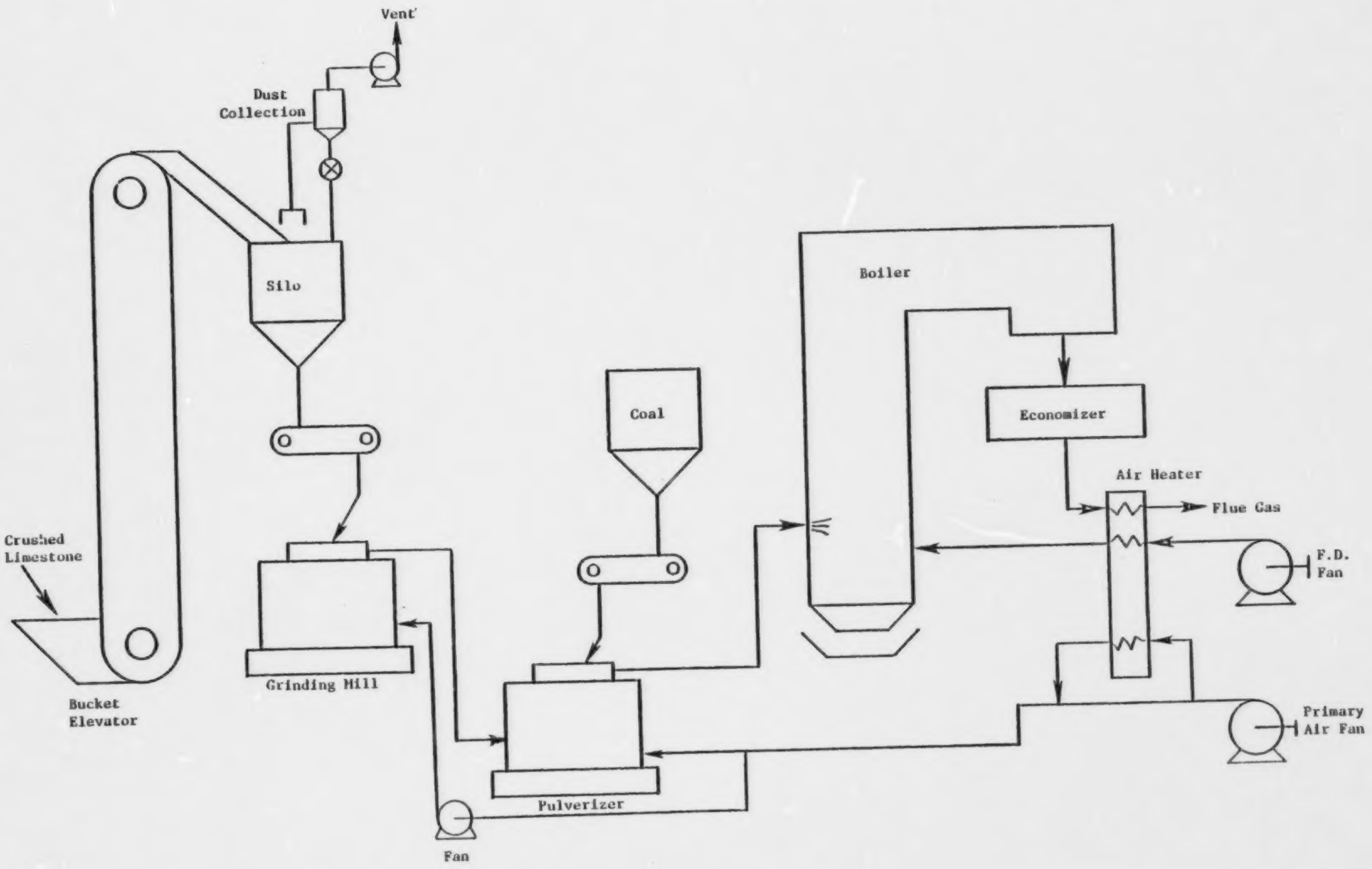
Vent
Dust
Collection
Silo
Crushed
Limestone
Bucket
Elevator
Grinding Mill
Fan
Coal
Pulverizer
Boiler
Economizer
Air Heater
Flue Gas
F.D.
Fan
Primary
Air Fan

Figure 7-2. Alternative B_1: Burner injection of ground limestone passed through coal pulverizers (local grinding).

TABLE 7-2. EQUIPMENT LIST AND POWER REQUIREMENTS FOR ALTERNATIVE B_1

Item	Electrical Power,[a] kW
Bucket Elevator, 23 m (75 ft) lift	2
Limestone Silo	-
Weigh-belt Feeder, Gravimetric	2
Limestone Grinding Mill, medium-speed, 99% through 325 mesh (44μ)	485
Primary Air Fan, 2:1 air/limestone mass ratio, ΔP net = 5.5 kPa (22 in. water)	49
Grinding Mill Air Fan, 2:1 air/limestone mass ratio, ΔP = 4.0 kPa (16 in. water) at 315°C (600°F)	67
Bag Filter and Fan, 3740 m^3/hr (2200 CFM)	6
Total	611

[a] Based on a limestone feed rate of 12 Mg/hr (13 tons/hr). This feedrate approximately represents the requirements of a 250 MWe boiler firing a 0.6% sulfur coal (Ca/S=4) or a 100 MWe boiler firing a 4.0% sulfur coal (Ca/S=2).

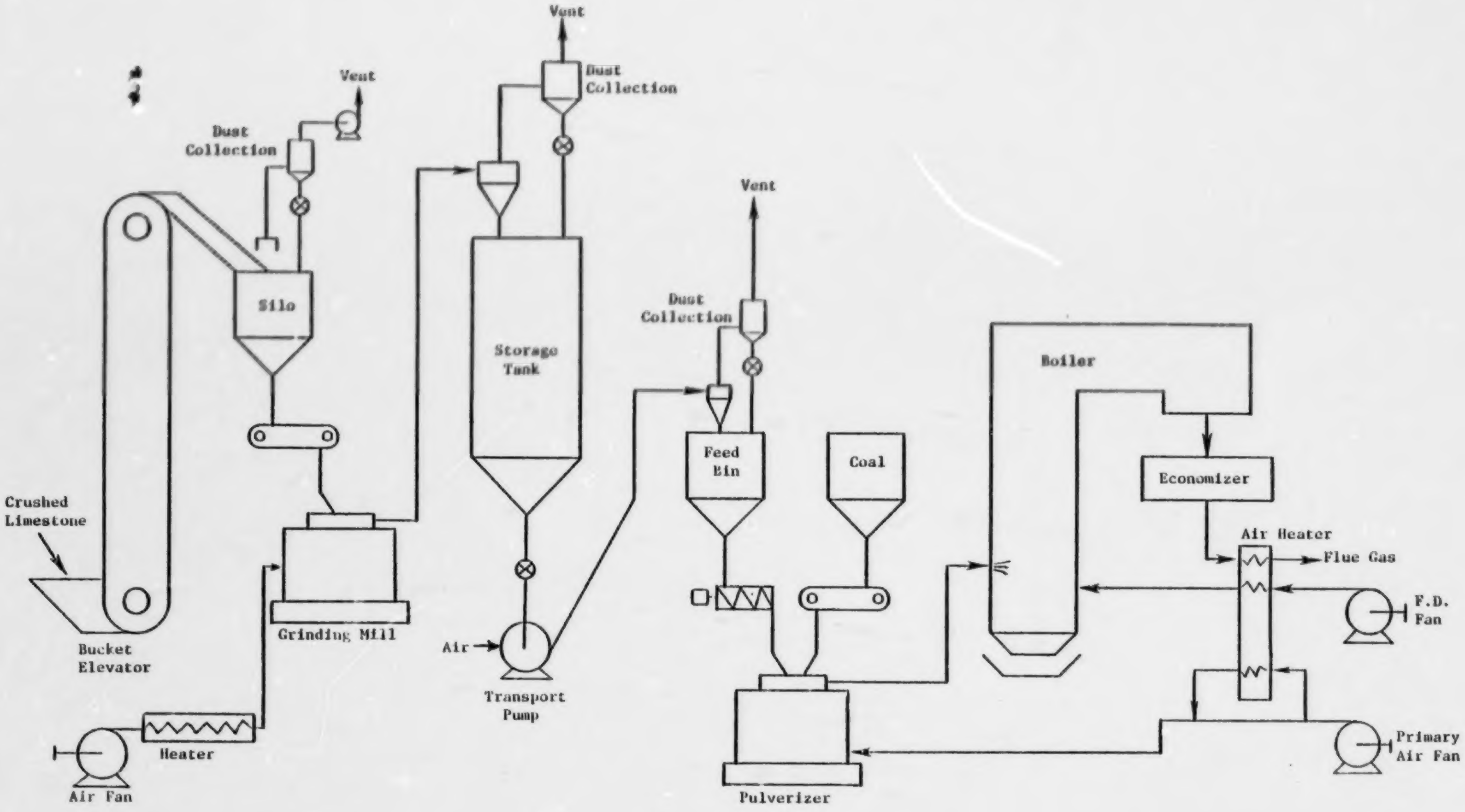
Vent
Dust Collection
Vent
Dust Collection
Silo
Storage Tank
Vent
Dust Collection
Feed Bin
Coal
Boiler
Economizer
Air Heater
Flue Gas
F.D. Fan
Crushed Limestone
Bucket Elevator
Grinding Mill
Air
Transport Pump
Primary Air Fan
Air Fan
Heater
Pulverizer

Figure 7-3. Alternative B_2: Burner injection of ground limestone passed through coal pulverizers (remote grinding).

TABLE 7-3. EQUIPMENT LIST AND POWER REQUIREMENTS FOR ALTERNATIVE B_2

Item	Electrical Power,[a] kW
Grinding	
Bucket Elevator, 23 m (75 ft) lift	2
Limestone Silo	-
Weigh-belt Feeder, Gravimetric	2
Limestone Grinding Mill, medium-speed, 99% through 325 mesh (44μ)	485
Grinding Mill Air Fan, 2:1 air/limestone ratio, ΔP = 7.7 kPa (31 in. water)	67
Air Heater	-
Bag Filter and Fan, 3740 m^3/hr (2200 CFM)	6
Storage	
Cyclone Separator	-
Bag Filter	-
Ground Limestone Storage Tank	-
Transfer	
Ground Limestone Transport, pneumatic and differential-pitch screw pump,[b]	10
Air Compressor,[b] 186 kPa (27 psig) maximum pressure	16
Cyclone Separator	-
Bag Filter	-
Injection	
Limestone Feed Bin	-
Screw Feeder[b]	3
Coal Pulverizer, mixing coal and limestone	10
Primary Air Fan, 2:1 air/limestone mass ratio, ΔP net = 5.5 kPa (22 in. water)	49
Total	650

[a] Based on a limestone feed rate of 12 Mg/hr (13 tons/hr). This feedrate approximately represents the requirements of a 250 MW_e boiler firing a 0.6% sulfur coal (Ca/S=4) or a 100 MW_e boiler firing a 4.0% sulfur coal (Ca/S=2).

[b] Reference 25.

study. Thus, it was assumed that mixing the two materials requires about five percent of the grinding energy requirements. The primary air fan power requirement increase is equal to that for Alternative A. The total energy requirements for arrangement B_2 are about 2.3 times that for Alternative A.

Advantages of Alternative B

There are three main advantages of this injection scheme. A separate grinding system could be specifically designed to handle limestone preparation. In multiboiler power plants, some savings might be provided by a remote central grinding system installed to supply prepared limestone to all the boilers. Also, this separate grinding system allows flexibility for design and control of the desired limestone particle fineness. For example, the limestone could be prepared to a fineness of 99 percent through 325 mesh (44μ) rather than the typical coal specification of only 60 to 80 percent through 200 mesh (74μ). Finally, as explained for Alternative A, this alternative offers the potential for good mixing of the limestone and coal particles in the coal pulverizer.

Disadvantages of Alternative B

This injection scheme would require a significant capital investment for the separate limestone grinding system, especially if the remote grinding arrangement (B_2) was employed. Space limitations in some existing power plants might preclude either arrangement of this injection scheme.

If none of the coal pulverizers firing the boiler have any excess capacity, the coal firing rate would have to be decreased somewhat. The boiler would be derated by the amount of capacity required for handling the mass of the separately ground limestone through the coal pulverizer. Coal pulverizer capacity would be limited mostly by increased loading on the classifier and only slightly by grinding capabilities.

The potential for decreased reliability and increased maintenance of the coal pulverizer and firing system, the lack of flexibility in the furnace injection point, and the impact of burner flame temperature on limestone reactivity are also potential disadvantages as discussed for Alternative A. This limestone injection scheme would have increased operating costs over that for Alternative A.

Historical Experience with Alternative B

There is no documented experience on this tandem limestone/coal preparation and injection scheme. However, four full-scale plant tests in which prepulverized limestone was mixed with the coal in the pulverizers have been documented. Two tests were conducted in the U. S. and two in Europe.

Kansas Power and Light Company conducted tests in 1968 with semi-ground (bird seed) limestone at the boiler site described under Alternative A.[12] Pulverizer power consumption for a raw coal/limestone mixed feed at a Ca/S ratio of 1.0 and a coal sulfur content of 3.1 percent was 18.5 kWh/Mg (16.8 kWh/ton) of material; the normal pulverizer power usage was noted to be 19.4 kWh/Mg (17.6 kWh/ton) of coal.

The second test in the U. S. was conducted by the U. S. Department of Energy in 1981 at the Otter Tail Power Company, Hoot Lake Station.[13,14] Preground limestone in the 6 to 100 mesh range was mixed with 0.7 percent sulfur lignite through the coal pulverizers and pneumatically conveyed through the burners of a 53 MW_e utility boiler. Ca/S ratios of 2.0 to 5.0 were used. At the higher injection rates pulverizer power consumption increased by nearly 20 percent over that experienced with no limestone injection. Numerous relatively large limestone particles up to about 50 mesh (300μ) were observed in samples of the pulverized coal/limestone mix from the pneumatic feed line between the pulverizer and the burners.

Other tests were conducted in West Germany and Austria during 1980 and 1981.[15,16] In the German tests, preground limestone of about 95 percent through 90 size was mixed with brown coal in the coal pulverizers of a 60 MW_e boiler. No problems were noted. The same results were obtained during the Austrian tests using a range of limestone particle sizes from about 95 percent less than 60μ down to 99.8 percent through 25μ.

ALTERNATIVE C: BURNER INJECTION OF GROUND LIMESTONE MIXED WITH PRIMARY AIR

For this alternative, limestone and coal are prepared separately, mixed, and pneumatically conveyed through the burners. Crushed limestone is ground separately to the desired particle size, as described in Alternative B. This injection scheme could be used with either the direct fired or bin coal preparation system. One of the major boiler manufacturers is now studying this limestone injection scheme on utility boilers.[17]

There are two possible arrangements for this injection scheme. First, the discharge streams from the coal pulverizer and separate limestone grinding mill could be mixed and jointly conveyed to the burner of a direct fired coal boiler. This simple first arrangement (C_1) is presented in Figure 7-4. As discussed for Alternative A and B, this arrangement would be acceptable only if the extra primary air could be handled through the burners.

If the extra primary air is not tolerable, a second arrangement could be employed to eliminate injection of the limestone conveying air. The ground limestone could be separated from its conveying air by a cyclone separator and bag filter. The separated ground limestone would collect in a feed tank located directly above the pneumatic coal feed lines to the burners and as close as possible to the boiler. The limestone

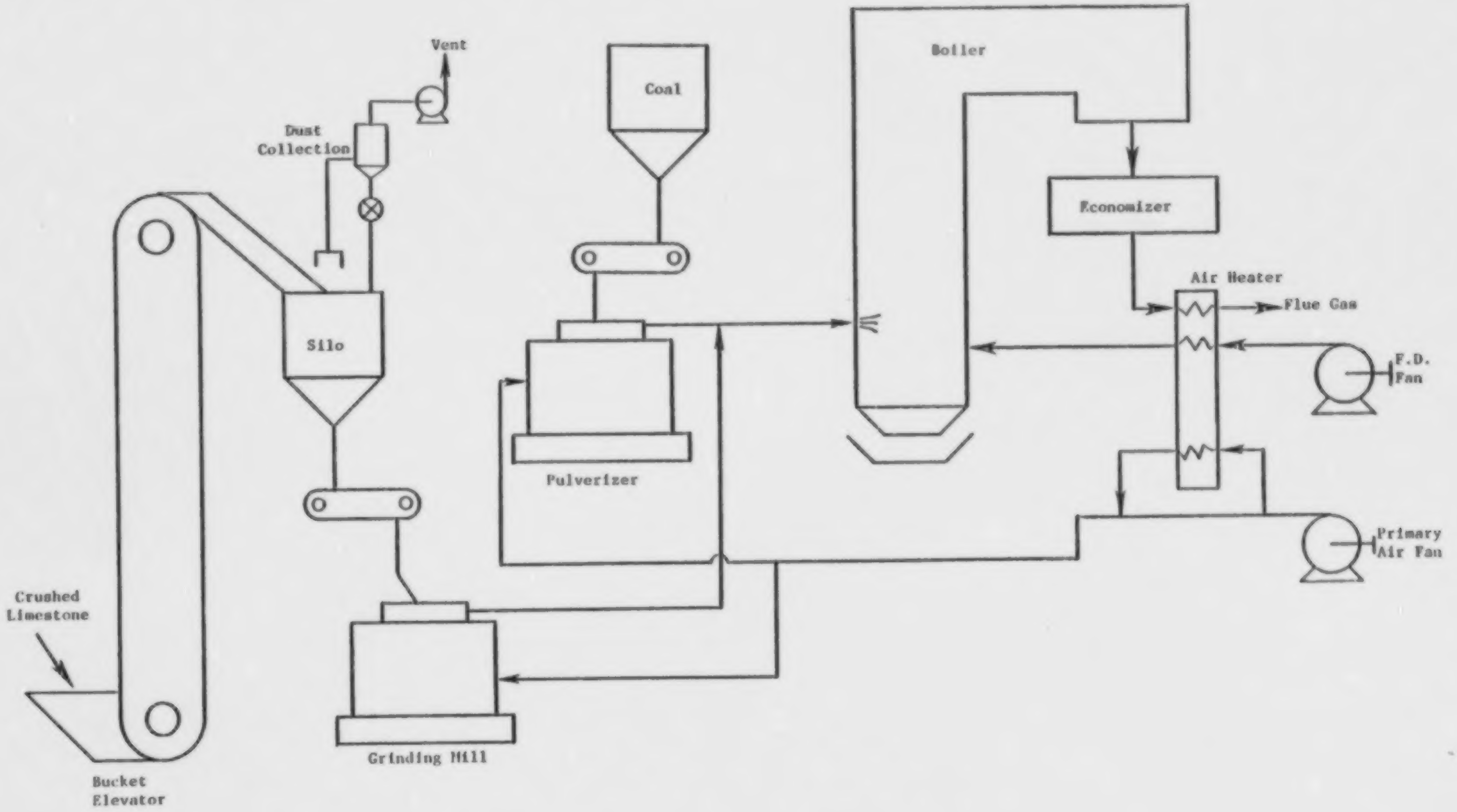
Vent
Dust Collection
Coal
Boiler
Economizer
Air Heater
Flue Gas
F.D. Fan
Primary Air Fan
Silo
Pulverizer
Crushed Limestone
Grinding Mill
Bucket Elevator

Figure 7-4. Alternative C_1: Burner injection of ground limestone mixed with primary air (joint conveying of coal and limestone).

would fall by gravity through a screw feeder and a rotary seal valve and into the burner feed lines. The momentum of the primary air and coal particles should be sufficient to carry the limestone particles through the burners, if the injection point is close enough to the burner. This second injection scheme (C_2) is presented in Figure 7-5.

The nominal power requirements for the second injection arrangement are presented in Table 7-4. Again, the coal firing rate is assumed to remain constant. The primary air requirements for preparation and injection of the limestone are complicated by the parallel flow of supplying air to both mills. The air flows to the mills would need to be balanced because of the different pressure drops through the pneumatic conveying lines for each mill. Also, it can be assumed that the extra primary air pressure drop for conveying limestone the very short distance to and through the burners will be only about 0.25 kPa (1 in. water). The total energy requirements for arrangement C_2 are slightly lower than for Alternative B_1, about twice that for Alternative A.

Advantages of Alternative C

As explained for Alternative B, this scheme has the advantage of a separate preparation system specifically designed for limestone properties and with the flexibility required to control particle size. An advantage over Alternatives A and B is that this injection scheme could be applied without affecting the preparation of coal. Coal pulverizer operation and maintenance are not affected. Boiler derating would be minimized since the coal firing rate could be maintained or increased slightly if extra pulverizer capacity were available. This alternative should also provide good mixing of the limestone and coal particles.

Disadvantages of Alternative C

The potential disadvantages of the primary air injection scheme would not necessarily occur at every boiler site. The separate limestone grinding system would require significant capital investment, and installation could be a problem at older plant sites with space limitations. Primary air flow through the burners would increase unless the conveying air from the separate grinding mill is separated from the limestone before injection. As discussed for Alternatives A and B, the impact of burner flame temperature on limestone reactivity is a potential problem.

Historical Experience with Alternative C

No documented experience with this separate limestone preparation/ primary air injection scheme was found.

ALTERNATIVE D: FURNACE INJECTION OF GROUND LIMESTONE

With this injection scheme limestone is prepared and injected independently of the coal/primary air firing system. Crushed limestone

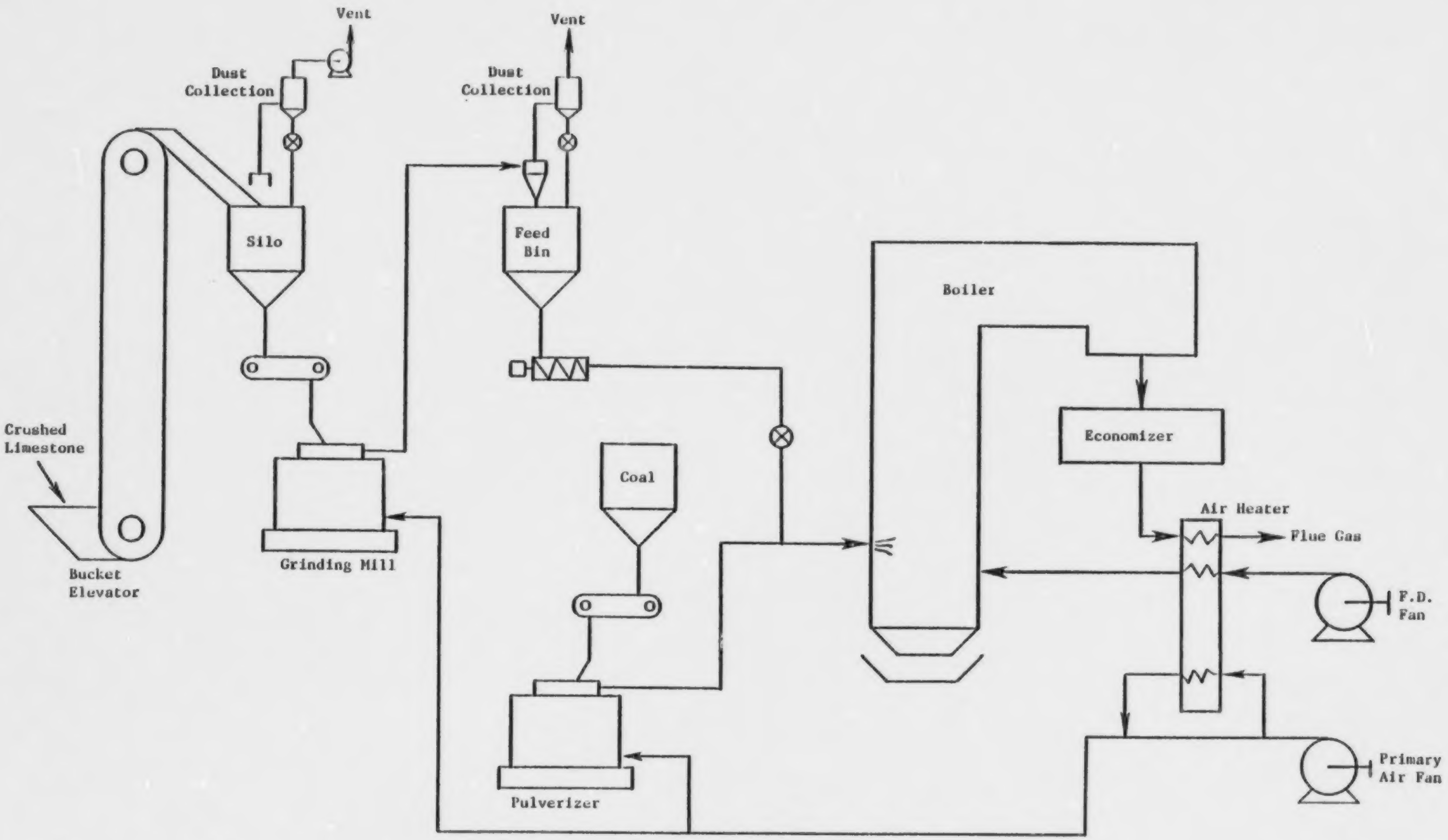
Vent
Vent
Dust
Collection
Dust
Collection
Silo
Feed
Bin
Boiler
Crushed
Limestone
Bucket
Elevator
Grinding Mill
Coal
Economizer
Air Heater
Flue Gas
F.D.
Fan
Pulverizer
Primary
Air Fan

Figure 7-5. Alternative C_2: Burner injection of ground limestone mixed with primary air (separation of limestone conveying air).

TABLE 7-4. EQUIPMENT LIST AND POWER REQUIREMENTS FOR ALTERNATIVE C_2

Item	Electrical Power,[a] kW
Bucket Elevator, 23 m (75 ft) lift	2
Limestone Silo	-
Weigh-belt Feeder, Gravimetric	2
Limestone Grinding Mill, medium-speed, 99% through 325 mesh (44μ)	485
Primary Air Fan, 2:1 air/limestone ratio, ΔP net = 5.7 kPa (23 in. water)	51
Bag Filter and Fan, 3740 m^3/hr (2200 CFM)	6
Limestone Feed Bin	-
Cyclone Separator	-
Bag Filter	-
Screw Feeder and Rotary Seal Valve[b]	6
Total	552

[a] Based on a limestone feed rate of 12 Mg/hr (13 tons/hr) This feedrate approximately represents the requirements of a 250 MW_e boiler firing a 0.6% sulfur coal (Ca/S=4) or a 100 MW_e boiler firing a 4.0% sulfur coal (Ca/S=2).

[b] Reference 25.

can be ground to any fineness desired, as with Alternatives B and C. The prepared limestone would be injected into the furnace at any of several points other than the coal nozzle. There are four possible arrangements for this injection scheme. Two injection options are available for application with either a local limestone preparation system near the boiler or a remote grinding system.

The most straightforward, arrangement would employ a local limestone preparation system and direct furnace injection through existing air ports. This technique could be applied only where sufficient space is available around the boiler. A separate limestone grinding mill could be installed next to the coal pulverizer and share part of the hot primary air supply. The conveying air and limestone from the mill would then be directly injected through the secondary and/or tertiary combustion air nozzles around the staged-air burners or through overfire air ports. Of course, the F.D. fan loading would be correspondingly decreased to maintain total combustion air to the furnace and minimize furnace upsets. This simple first arrangement (D_1) is presented in Figure 7-6.

A second independent arrangement could be employed if injection at other points in the furnace is desired. The ground limestone from the mill is transferred to a feed tank and separated from its conveying air, as described for Alternative C. Dense phase, pressurized air injection is used to inject the sorbent through other ports installed at various points on the furnace walls. An air compressor is required to provide the transport and injection medium at a pressure of at least 140 kPa (20 psi) gauge. This local pressurized air injection arrangement (D_2) is presented in Figure 7-7.

The nominal power requirements for injection arrangement D_2 are presented in Table 7-5. Again, the coal firing rate is assumed to remain constant. Energy required for limestone grinding is equal to that for Alternatives B and C. A balanced parallel primary air supply is required for the two grinding mills. The primary air energy requirements are equal to that for Alternatives A and B_2. The total transport and injection pressurized air supply requires an air to limestone mass ratio of 2:13.[18] The total energy requirements for arrangement D_2 are slightly more than double that for Alternative A.

If the first two arrangements are not feasible, two more costly and complex arrangements would require a remote limestone preparation system. A central limestone grinding system, as described for Alternative B (arrangement 2), might be the best arrangement where there are local space limitations around the boilers or where limestone injection is to be applied at a multiboiler plant. The prepared limestone could be transferred to a feed tank and separated from the conveying air. Pressurized-air could then be used for dense phase furnace injection, as described for the previous arrangement. Also, the F.D. fan combustion air could be employed to convey the limestone through secondary or tertiary combustion air nozzles. A remote, central limestone preparation system with a combustion air injection arrangement (D_3) is presented in Figure 7-8.

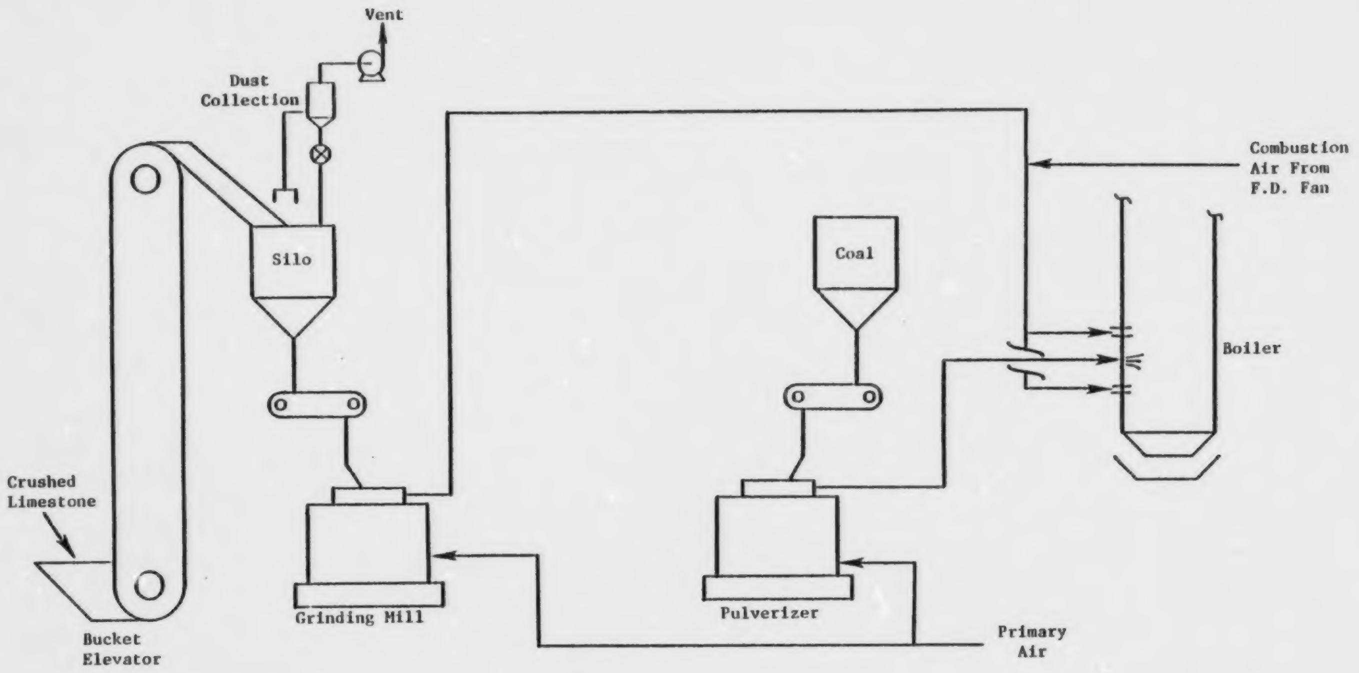
Vent
Dust Collection
Silo
Crushed Limestone
Bucket Elevator
Grinding Mill
Coal
Pulverizer
Primary Air
Combustion Air From F.D. Fan
Boiler

Figure 7-6. Alternative D_1: Furnace injection of ground limestone with combustion air (local grinding).

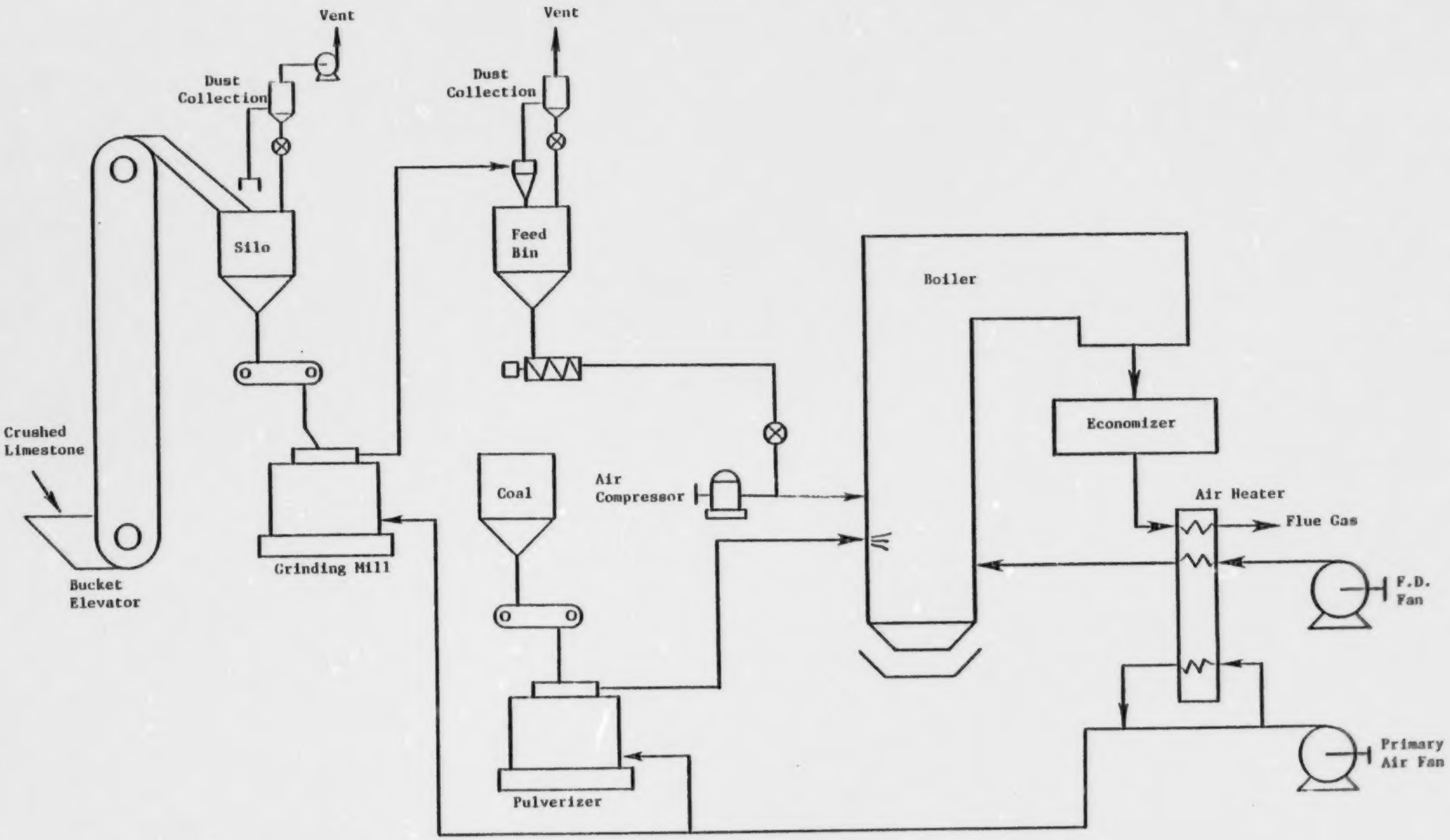
Vent
Dust Collection
Vent
Dust Collection
Silo
Feed Bin
Boiler
Crushed Limestone
Economizer
Air Compressor
Coal
Air Heater
Flue Gas
Bucket Elevator
Grinding Mill
F.D. Fan
Primary Air Fan
Pulverizer

Figure 7-7. Alternative D_2: Furnace injection of ground limestone with pressurized air (local grinding).

TABLE 7-5. EQUIPMENT LIST AND POWER REQUIREMENTS FOR ALTERNATIVE D_2

Item	Electrical Power,[a] kW
Bucket Elevator, 23 m (75 ft) lift	2
Limestone Silo	-
Weigh-belt Feeder, Gravimetric	2
Limestone Grinding Mill, medium-speed, 99% through 325 mesh (44μ)	485
Primary Air Fan, 2:1 air/limestone ratio, ΔP net = 5.5 kPa (22 in. water)	49
Bag Filter and Fan, 3740 m^3/hr (2200 CFM)	6
Limestone Feed Bin	-
Cyclone Separator	-
Bag Filter	-
Screw Feeder and Rotary Seal Valve[b]	6
Air Compressor, 2:13 air/limestone ratio,[c] ΔP = 140 kPa (20 psi)	53
Total	603

[a] Based on a limestone feed rate of 12 Mg/hr (13 tons/hr). This feedrate approximately represents the requirements of a 250 MW_e boiler firing a 0.6% sulfur coal (Ca/S=4) or a 100 MW_e boiler firing a 4.0% sulfur coal (Ca/S=2).

[b] Reference 25.

[c] Reference 18.

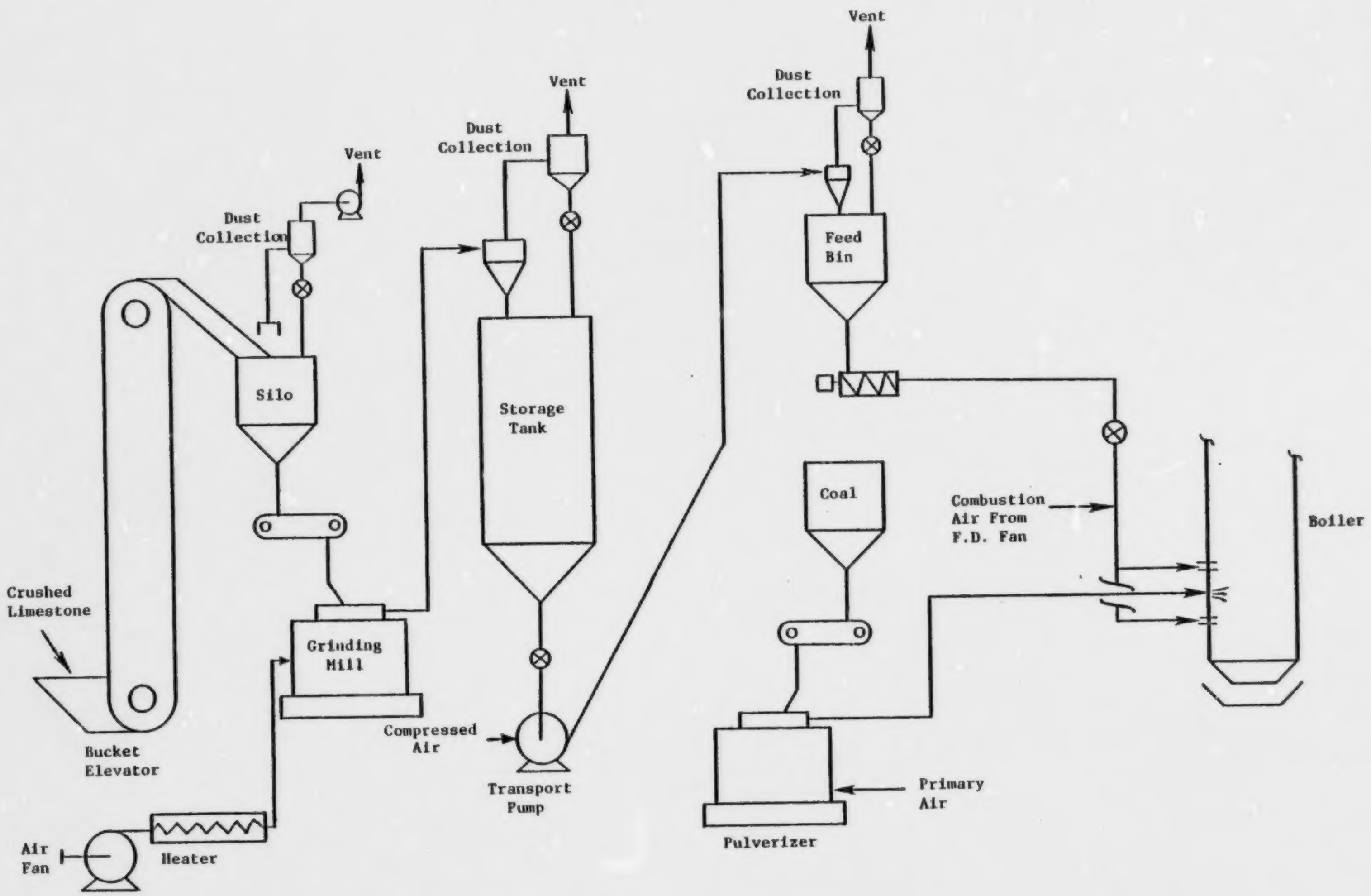
Vent
Dust Collection
Vent
Dust Collection
Vent
Dust Collection
Feed Bin
Silo
Storage Tank
Coal
Combustion Air From F.D. Fan
Boiler
Crushed Limestone
Grinding Mill
Bucket Elevator
Compressed Air
Transport Pump
Primary Air
Pulverizer
Air Fan
Heater

Figure 7-8. Alternative D_3: Furnace injection of ground limestone with combustion air (remote grinding).

The nominal power requirements for injection arrangement D_3 are presented in Table 7-6. Again, the coal firing rate is assumed to remain constant. The limestone grinding, storage, and transfer power requirements are equal to those shown in Table 7-3 for Alternative B_2. As with Alternative C_2, it is assumed that the F.D. fan discharge pressure increases about 0.25 kPa (1 in. water) for limestone injection. There are no primary air fan impacts. The total energy requirements are slightly more than twice that for Alternative A.

Advantages of Alternative D

This independent injection scheme shares several advantages with other alternatives. As explained for Alternatives B and C, a separate limestone preparation system could be designed and the limestone particle fineness could be controlled. As for Alternative C, this injection scheme could be applied with any type coal since the coal pulverizer operation and maintenance are unaffected. An additional advantage is that the coal firing performance would be unaffected. Finally, this injection scheme allows flexibility in selection of the furnace injection point. This technique could be used to selectively inject the limestone in various parts of the furnace to maximize SO_x control efficiency.

Disadvantages of Alternative D

Two potential disadvantages with independent furnace injection are as follows. As discussed for Alternative B and C, the separate limestone preparation system would require significant capital investment and installation may be a problem in older plant sites with space limitations. In addition, a complex air injection system with installation of injection nozzles in the furnace walls or combustion air system would be necessary. Another potential problem with independent injection is incomplete limestone distribution in the flue gas and interation with sulfur oxides.

Historical Experience with Alternative D

Preparation and furnace injection of limestone independently of the coal/primary air firing system has been documented for full-scale boilers at four utilities in the U. S. These include Union Electric, Kansas Power and Light, Kansas City Power and Light, and TVA. Recent European pilot-scale tests have also been reported.

Union Electric Company continuously injected limestone or dolomite in a 140 MW_e boiler at its Meramec plant from 1968 through 1971.[19,20,21] The boiler was fired with a midwestern bituminous coal containing over three percent sulfur and nine percent ash. Crushed limestone or dolomite was stored in a partitioned section of the coal bunker, and a spare pulverizer was used to grind the stone. Sorbent was directly injected at a Ca-Mg/S ratio of 0.6 to 1.3 through spare burners located above the operating burners. After only one month of operation, the limestone grinding mill required complete overhaul. No other limestone preparation and injection handling problems were noted.

TABLE 7-6. EQUIPMENT LIST AND POWER REQUIREMENTS FOR ALTERNATIVE D_3

Item	Electrical Power,[a] kW
Grinding	
Bucket Elevator, 23 m (75 ft) lift	2
Limestone Silo	-
Weigh-belt Feeder, Gravimetric	2
Limestone Grinding Mill, medium-speed, 99% through 325 mesh (44μ)	485
Grinding Mill Air Fan, 2:1 air/limestone ratio, ΔP = 7.7 kPa (31 in. water)	67
Air Heater	-
Bag Filter and Fan, 3740 m^3/hr (2200 CFM)	6
Storage	
Cyclone Separator	-
Bag Filter	-
Ground Limestone Storage Tank	-
Transfer	
Ground Limestone Transport, pneumatic and differential-pitch screw pump[b]	10
Air Compressor,[b] 190 kPa (27 psig) maximum pressure	16
Cyclone Separator	-
Bag Filter	-
Injection	
Limestone Feed Bin	-
Screw Feeder and Rotary Seal Valve[b]	6
Forced Draft Fan, 2:1 air/limestone mass ratio, ΔP net = 0.25 kPa (1 in. water)	6
Total	600

[a] Based on a limestone feed rate of 12 Mg/hr (13 tons/hr). This feedrate approximately represents the requirements of a 250 MW_e boiler firing a 0.6% sulfur coal (Ca/S=4) or a 100 MW_e boiler firing a 4.0% sulfur coal (Ca/S=2).

[b] Reference 25.

Kansas Power and Light Company continuously injected limestone in a 420 MW_e boiler (unit 5) at its Lawrence Station from 1971 to 1975.[22,23] This boiler used the same fuel (3 percent sulfur, 8-10 percent ash) as unit 4 described under the experience with Alternative A. A spare pulverizer was used to grind the stone at a Ca/S ratio of 1.0 to 1.5. The sorbent was directly injected through spare nozzles located above the coal burners. A slight increase in the wear of the grinding elements was noted when the spare pulverizer was used for limestone instead of coal. No other preparation and injection handling problems were noted.

Kansas City Power and Light Company continuously injected limestone in two 100 MW_e boilers at its Hawthorn Station from 1972 to 1975.[24] Two coals were fired: a 3 percent sulfur, 14 percent ash midwest bituminous coal and a 0.6 percent sulfur, 11 percent ash subbituminous coal. Spare pulverizers were used to grind the stone at Ca/S ratios of 1.0 to 1.1 and directly inject the sorbent in the furnaces. Excessive wear on pulverizer rolls and balls required readjustment of the roll height above the race.

TVA conducted several months of limestone injection tests in a 150 MW_e boiler at its Shawnee plant during 1970 and 1971.[25] A 2.7 percent sulfur, 12 percent ash Kentucky coal was fired. A remote limestone preparation system employed a ball mill with an external classifier. Three limestone types were handled: Marl, Fredonia, and Aragonite. The latter two had relatively low moisture content; however, the Marl was received with a moisture content of over 50 percent and was very difficult to handle. The crushed limestone was ground to a fineness of 70 to 95 percent through 325 mesh (44μ) and stored in a silo. Full capacity of the ball mill and classifier at 18 Mg (20 tons) per hour was achievable at only the coarse particle size; operating rate decreased to 8 Mg (9 tons) per hour for the fine product size.

The ground limestone was transferred as needed to an injection feed tank near the boiler. A cascade pressurized air system at 140 kPa (20 psi) gauge was employed to feed the limestone. The sorbent was pneumatically transported in dense phase to a splitter vessel where it was distributed through mixing tubes and injected with additional air at three points around the furnace: below, above, and across from the wall fired burners. Ca/S ratios of 1.0 and 2.0 were tried. Tests were conducted with injection velocities of 18 to 40 m/sec (60 to 130 ft/sec) and the injection nozzles oriented downward, horizontal, and upwards. However, furnace turbulence was found to be the overriding influence on distribution of the particles. In these tests the particles rapidly mixed with the gas and assumed a similar distribution profile as the SO_2. Use of separate injection air just before the furnace nozzle to boost final velocity did not operate well and was not recommended for future tests.

Pilot-scale studies with independent limestone injection were conducted by the International Flame Research Foundation (IFRF) in Holland during 1980 and 1981.[26] Limestone was injected with the combustion air through tertiary air ports of a staged air burner. No injection problems were noted.

OTHER ALTERNATIVES

Several variations of the above alternatives are also possible. For example, an injection scheme to minimize capital investment could involve the purchase of prepulverized rather than crushed limestone. No limestone preparation system would be required and the problem of space limitations would be avoided. Of course, the purchase cost of 200 to 325 mesh prepulverized limestone ranges from two to six times that of crushed limestone.[27] Thus, for long term operation the lower capital costs might be more than offset by higher operating costs. The prepulverized sorbent could be handled via any of the injection schemes for Alternatives B, C, or D. Operating experience with prepulverized limestone has been documented in several tests, as discussed for Alternatives B and D.

The most flexible injection scheme could involve a combination of any of the discussed alternatives. For example, if a coal pulverizer has some extra capacity available, a portion of the limestone could be mixed with the coal while the remainder was injected with the combustion air or through other ports in the furnace walls. The advantages of each of the alternatives could be incorporated to result in the combination scheme best suited for site specific situations. Potential disadvantages of combining injection alternatives could include complication in control of the limestone feed and combustion air rates.

ENERGY IMPACT SUMMARY

A summary of the specific electrical power requirements for handling, pulverizing, and injecting limestone on a unit mass basis by the various alternative schemes is presented in Table 7-7. Other boiler thermal energy impacts are presented in Section 9. Alternative A, which involves pulverizing crushed limestone and coal together, has the lowest energy consumption; however, the achievable sorbent particle size is limited by the coal preparation specification. In comparison, the results of the TVA tests with a remote ball mill limestone preparation system show much higher power requirements.

Some example energy impacts for a high sulfur bituminous coal case and a low sulfur subbituminous coal case are presented in Table 7-8. Impacts for the high sulfur coal case are about three times those for the low sulfur case. However, in either case the coal firing rate would need to be increased by less than one percent to maintain the boiler net electrical power output.

TABLE 7-7. SUMMARY OF SPECIFIC ELECTRICAL POWER REQUIREMENTS FOR LIMESTONE HANDLING, PREPARATION, AND INJECTION ALTERNATIVES

Alternative	Limestone Grinding Mill	Limestone Particle Size %, - Mesh Size (μ)	Specific Power Requirements[a] kWh/Mg	(kWh/ton)
A	Medium-Speed Mill Coal Pulverizer	75, - 200 (74)	32	(29)
B_1	Separate Medium-Speed Mill	99, - 325 (44)	59	(55)
B_2	Separate Medium-Speed Mill	99, - 325 (44)	62	(58)
C_2	Separate Medium-Speed Mill	99, - 325 (44)	54	(50)
D_2	Separate Medium-Speed Mill	99, - 325 (44)	58	(54)
D_3	Separate Medium-Speed Mill	99, - 325 (44)	58	(54)
TVA Tests[b]	Separate Ball Mill	70, - 325 (44)	76	(69)

[a] Totals from Tables 6-2 and 7-1 through 7-6.

[b] Reference 28.

TABLE 7-8. LIMESTONE PREPARATION AND INJECTION ELECTRICAL POWER REQUIREMENTS FOR BOILERS FIRING HIGH AND LOW SULFUR COALS

Coal	Ca/S	Energy Consumption[a] Coal Basis $\frac{kWh}{Mg}$	Energy Consumption[a] Coal Basis $\frac{kWh}{ton}$	Increased Coal Consumption[b] to Maintain Boiler Load
Montana Subbituminous 0.6% sulfur HHV = 19, 930 J/g (8,570 Btu/lb)	4	4.9	(4.4)	0.26%
Illinois Bituminous 4.0% sulfur HHV = 23,480 J/g (10,100 Btu/lb)	2	16.3	(14.8)	0.73%

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[a] From Table 7-7, assume 50 kWh/ton limestone with limestone to coal ratio from Table 6-1.

[b] Boiler coal-to-electric heat rate assumed to be 10.5×10^6 J/kWh (10,000 Btu/kWh).

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9. Reference 4.

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SECTION 8

BOILER DESIGN AND OPERATION

The boiler system is the second major subsystem evaluated as part of this systems analysis. This section presents the boiler design and operation principles needed to understand and evaluate the applicability of LIMB. A general description of boiler components and their functions is presented. The design and operation of the furnace and convection sections are discussed. Specific methods of controlling slagging and fouling are presented. Finally, the design profile of the existing boiler population is described.

BOILER SYSTEM COMPONENTS

Modern coal fired steam generating units consist of components designed to burn the coal, absorb heat from the combustion product gases, and remove ash residue from the unit. Coal combustion components include the burners and the furnace enclosure. Heat absorption or recovery components include the boiler (or furnace wall tubes), superheater, reheater, economizer, and air heater. Sootblowers; bottom, economizer, and air heater ash hoppers; and ash removal equipment comprise the ash removal components. The boiler system, as defined in this report, includes all of these components. Figure 8-1 illustrates the arrangement of major boiler system components for a large utility pulverized coal unit.

Combustion

In a pulverized coal boiler the combustion process occurs within a rectangular enclosure called the furnace. Finely pulverized coal is pneumatically injected through burners located on the furnace walls. Combustion air is injected through the burners and through secondary or overfire air ports. The flame begins near the coal nozzles extending outward into the furnace. One of the key aspects of furnace design is to provide sufficient volume for complete combustion of the coal particles.

The combustion process causes a rapid release of large quantities of heat resulting in high gas temperatures within the furnace. For example, furnace gas temperatures commonly range from 1100-1600°C (2000-3000°F). Actual temperatures depend on the volume available for heat release and on the available heat absorption area.

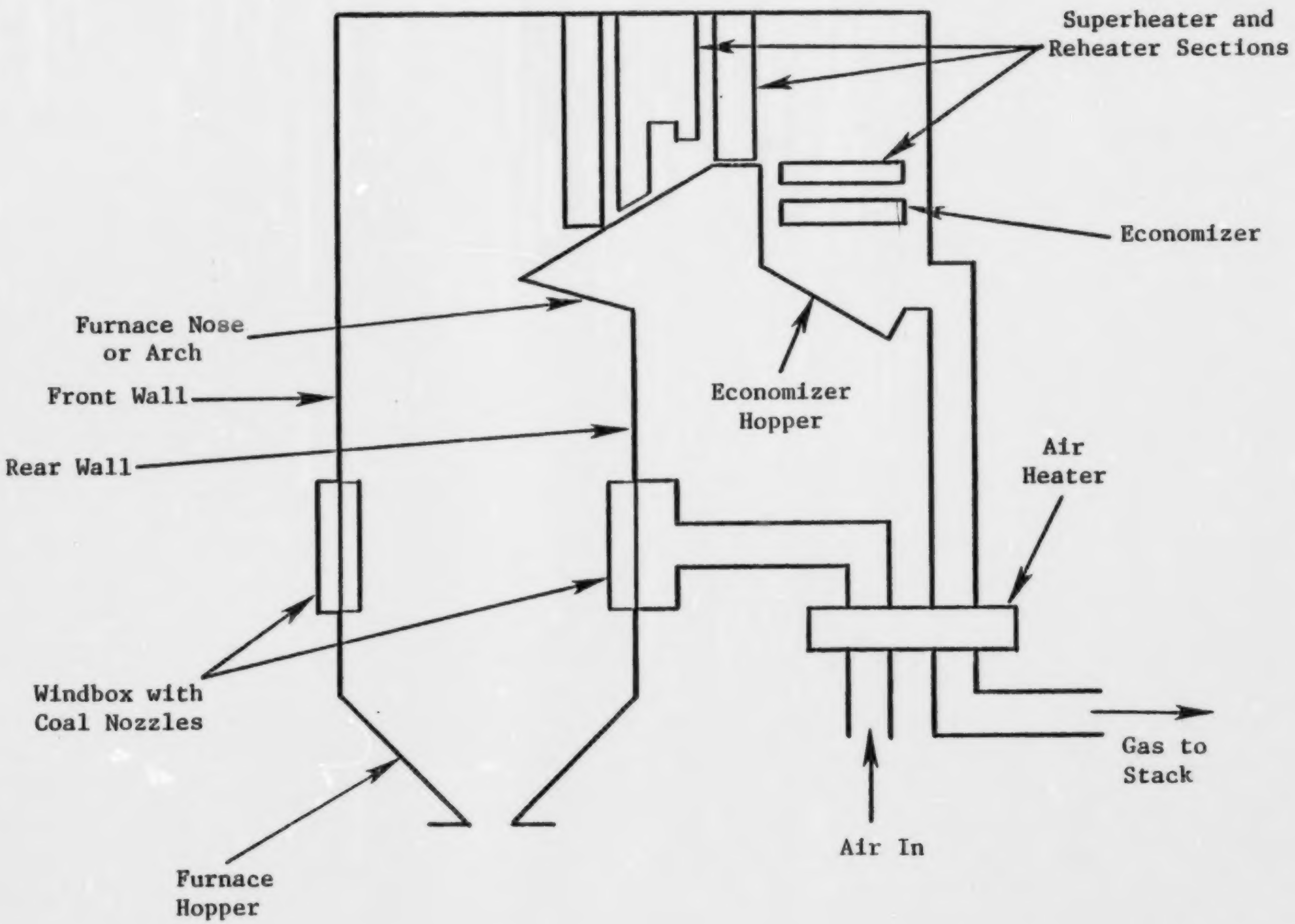
Superheater and
Reheater Sections
Economizer
Furnace Nose
or Arch
Front Wall
Economizer
Hopper
Rear Wall
Air
Heater
Windbox with
Coal Nozzles
Gas to
Stack
Air In
Furnace
Hopper

Figure 8-1. Arrangement of major boiler system components in a large pulverized coal boiler.

Heat Absorption and Transfer

The furnace wall tubes (boiler), superheater, reheater, and economizer components are arranged for efficient heat absorption and steam generation. Another component, the air heater, does not directly absorb heat to produce steam. Rather, it transfers low temperature heat that would otherwise be lost out the stack back to the furnace via the combustion air.

The design of each of these components depends on the properties of the coal selected and on the end use to which the steam generator will be put. Smaller industrial boilers may lack the reheater, economizer or air heater. However, the paramount importance of thermal efficiency requires the use of all of these components in utility units.

As the flue gas contacts each component, the gas temperature is lowered as heat is absorbed or transferred. An example combustion gas temperature profile for a large utility unit is presented in Figure 8-2. This profile represents equipment/temperature relationships typical of many large units, but the actual profile for a given unit can vary significantly.

The term "boiler" is often used to refer to the entire steam generating unit. However, in a narrower sense the boiler is the portion of the unit where most of the steam is generated. Babcock and Wilcox[1] defines boiler surface as "those parts of the tubes, drums, and shells which are part of the boiler circulatory system and which are in contact with the hot gases on one side and water or a mixture of water and steam on the other side". In a large modern unit the boiler consists mainly of waterwall tubes lining the walls of the furnace.

As discussed previously, furnace wall tubes are exposed to extremely hot combustion gases. As a result, these tubes are potentially subject to slagging problems. "Slagging" is an accumulation of slag or ash resulting from the physical transport of molten ash particles to tube surfaces. Slagging occurs primarily on furnace wall tubes or on some of the initial superheater tubes located prior to the tightly spaced convection passes. To reduce slagging problems most furnaces are designed to minimize direct contact of the hot gases with the wall tubes. Instead, the combustion gases are cooled primarily through radiation of heat to the wall tubes. Since radiation is the principal means of heat transfer, this portion of a steam generating unit is often referred to as the "radiant section".

Combustion gases leaving the furnace are so cool that radiation is no longer an efficient form of heat transfer. Heat transfer occurs by convection in the rest of the unit, and this portion is called the "convection section". To provide for efficient convective heat transfer the surfaces are spaced relatively close together and in direct contact with the flow of combustion gases. As the combustion gases cool through

POINT	TEMP.,°F.
1	300
2	600
3	750
4	825
5	950
6	1200
7	1575
8	1780
9	1900
10	2100
11	>3000

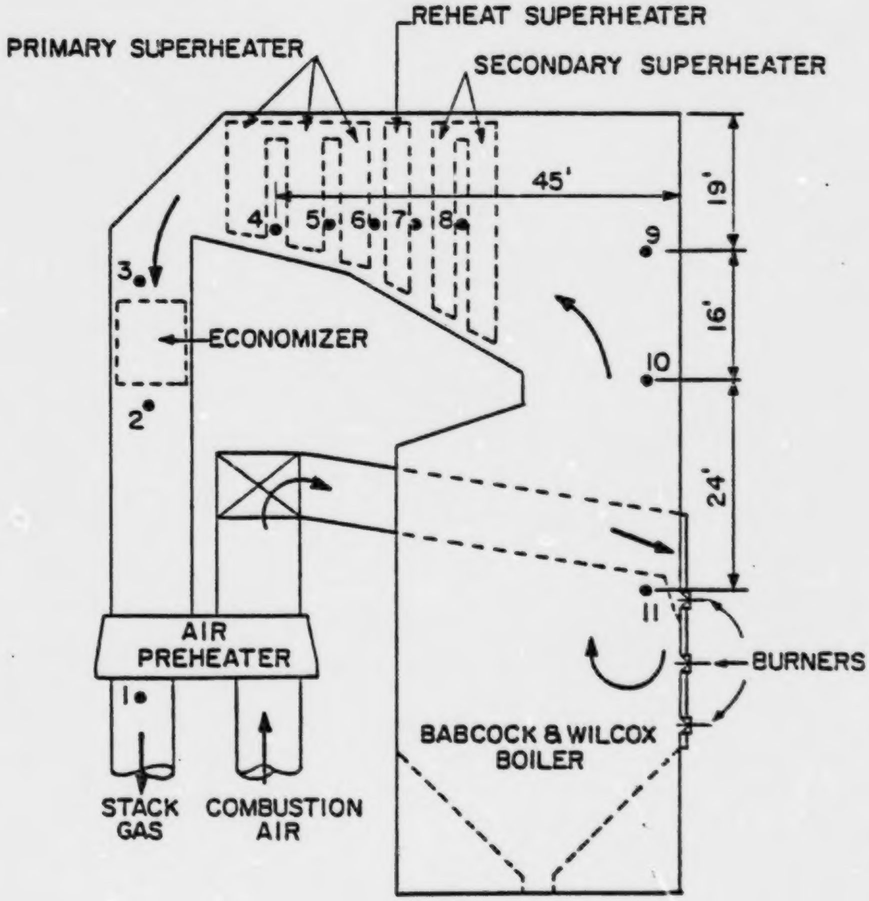
REHEAT SUPERHEATER
PRIMARY SUPERHEATER
SECONDARY SUPERHEATER
45'
19'
16'
24'
1
2
3
4
5
6
7
8
9
10
11
ECONOMIZER
AIR PREHEATER
STACK GAS
COMBUSTION AIR
BURNERS
BABCOCK & WILCOX BOILER

Figure 8-2. Example flue gas temperature profile through the boiler system.[a,b]

[a] Reference 2.

[b] °C = (°F-32)/1.8
m = ft/3.281

the convection section, the heat transfer surfaces are spaced progressively closer together. The actual spacings depend on heat transfer rate, ash deposition rate, flue gas velocity, and ash abrasiveness.

Ash deposition in the convection section is called "fouling". Fouling generally results from a different mechanism than slagging. Fouling is caused by the condensation of volatile ash constituents on tube surfaces and other ash particles thereby conditioning the particles for retention.

The initial heat transfer components of the convection section are the superheater and reheater, which absorb heat from the combustion gases to provide "superheat" to the steam. While both components absorb heat to raise the steam temperature above its saturation level, they treat steam of considerably different pressures from different sources.

The superheater provides superheat to the high pressure steam originating in the furnace wall tubes. In utility boilers, steam from the superheaters is then fed to high pressure turbines to drive the generators thereby producing electricity. The reheater provides superheat to steam extracted from the high pressure turbines. This steam has been reduced in both temperature and pressure from that originally exiting the superheater. By reheating, or increasing the temperature of this steam, the reheater allows the available steam energy to be more efficiently used in lower pressure turbines.

The economizer is also located in the convection section downstream of the superheater and reheater. Combustion gases reaching the economizer have been considerably cooled by the superheater and reheater and are no longer suitable for providing superheat to the steam. However, these gases still contain considerable quantities of useful heat. The economizer recovers a portion of this heat and preheats the boiler feedwater. In some units so much heat is absorbed in the economizer that a portion of the steam output is actually generated there.

The final heat transfer component of the convection section is the air heater. This device plays no role in the absorption of heat to produce steam. Instead, it transfers heat from one portion of the unit to another. Heat is recovered from the relatively low temperature combustion gases prior to discharge and transferred to the combustion air where it enters the furnace. Heat recovery at the air heater is often limited by the necessity to avoid cooling the flue gas through its acid dew point.

Removal of Ash Residue

Among the many elements and compounds present in coal is a noncombustible fraction called ash. In most pulverized coal units, about 60 to 80 percent of the ash is entrained by the combustion gases and leaves the furnace as fly ash. Some fly ash is retained in the convection section, depositing on heat transfer surfaces or collecting in hoppers associated with the economizer and air heater. Ash retained in the furnace is either deposited on the furnace walls or falls to the bottom of the unit.

Retained ash can interfere with heat transfer, cause excessive corrosion of tube surfaces, and block flue gas passageways through the convection section. Thus, for the boiler system to function properly retained ash must be removed from the system. Boiler system components designed for this purpose include sootblowers and ash removal systems for the furnace bottom, economizer, and air heater ash hoppers.

Sootblowers control the buildup of ash deposits on furnace walls and convection pass surfaces by directing a jet of steam, hot air, or water at the deposits to dislodge them. The deposits are reentrained by the flue gas or settle into collection hoppers. Sootblowers can be operated either manually or automatically.

To collect ash falling or settling in the boiler system, hoppers are provided below the furnace, economizer, and air heater. Each hopper is equipped with a removal system to prevent ash backup into the boiler system. The removal systems may operate intermittently or continuously and be of mechanical, hydraulic, or pneumatic design.

FURNACE DESIGN AND OPERATION

The primary functions of a furnace are to burn the coal completely and to control the temperature of gases entering the closely spaced convective passes. Complete combustion within the furnace is necessary since rapid cooling in the convection section effectively halts further combustion reactions. Control of combustion gas temperature is important for steam temperature control and to aid cleaning in the convection section .

This section discusses the principles of furnace design and operation. Major furnace design types are described, design criteria for sizing and operating the furnace are presented, and methods of removing furnace bottom ash are discussed.

Types of Furnaces

Furnaces for pulverized coal boilers in the United States exist in a variety of designs. Designs differ mainly in fuel firing systems and methods of ash collection. These differences result from the design preferences of individual boiler manufacturers and from the coal properties for which individual units were designed.

The two major firing system designs for pulverized coal units in the United States are the horizontally or wall fired system and the tangentially fired system. Tangentially fired systems are designed by Combustion Engineering while wall fired systems are principally designed by the other major manufacturers. A third firing system design is the vertically or arch fired system. However, this design is only used today to fire solid fuels that are difficult to ignite, such as coals with very low volatile matter content (i.e. anthracite).[3]

With wall fired systems, burners are located in rows, either along the front wall or along the front and rear walls. The first method is called one wall or front wall firing and the latter opposed firing. One wall fired units are common in the smaller unit sizes but opposed firing predominates on a total capacity basis. Table 8-1 presents sales data compiled by Babcock and Wilcox showing the relative distributions of one wall and opposed firing systems.

In wall fired furnaces coal and air are mixed and burned through individual burners with little interaction between separate burners. Each burner is designed to impart a strong rotation to the coal and primary air exiting the coal nozzle and to the secondary air exiting surrounding air registers. A relatively tight recirculation pattern of coal, air, and hot combustion product gases is established for each burner. The major portion of the combustion process occurs within this recirculation zone. A schematic of an opposed firing system is provided in Figure 8-3.

With increased interest in NO_x control beginning in the early 1970s, burner designs were altered to slow the mixing of coal and combustion air by installing multiple air registers and adjusting the degree of swirl. These modifications have effectively increased the length of the recirculation or combustion zone extending from each burner. Recently built furnaces have been designed to accomodate the increased combustion zone size requirements of these new burner designs. However, as discussed later, many existing units designed for older style burners still have relatively small combustion zones.

A wall firing system design which slows the combustion process even further is under development by EPA. The distributed mixing burner design diverts a portion of the combustion air through separate tertiary air ports spaced symmetrically around the burners on the furnace walls. This design was discussed in Section 4 and a schematic is presented in Figure 4-1.

With tangentially fired systems, burners are located in each of the four corners of the furnace at multiple elevations. Each burner projects a flame on the tangent of an imaginary horizontal circle in the middle of the furnace. A schematic showing a plan view of this firing system design is presented in Figure 8-4.

At each burner level, coal and primary air are injected through coal nozzles located in each corner of the furnace. Secondary air is injected through separate air nozzles located at elevations above and below the coal nozzles. The result is effectively a single flame envelope

TABLE 8-1. FIRING PATTERN DISTRIBUTION FOR WALL FIRED UNITS - SALES DATA COMPILED BY BABCOCK AND WILCOX[4]

Firing Pattern/Unit Size	% of Units	% of Steam Flow
One wall firing/all units	42.9	8.8
Opposed firing/units <300 MW	8.0	5.3
Opposed firing/units 300 to 600 MW	22.3	27.7
Opposed firing/units >600 MW	26.8	58.2

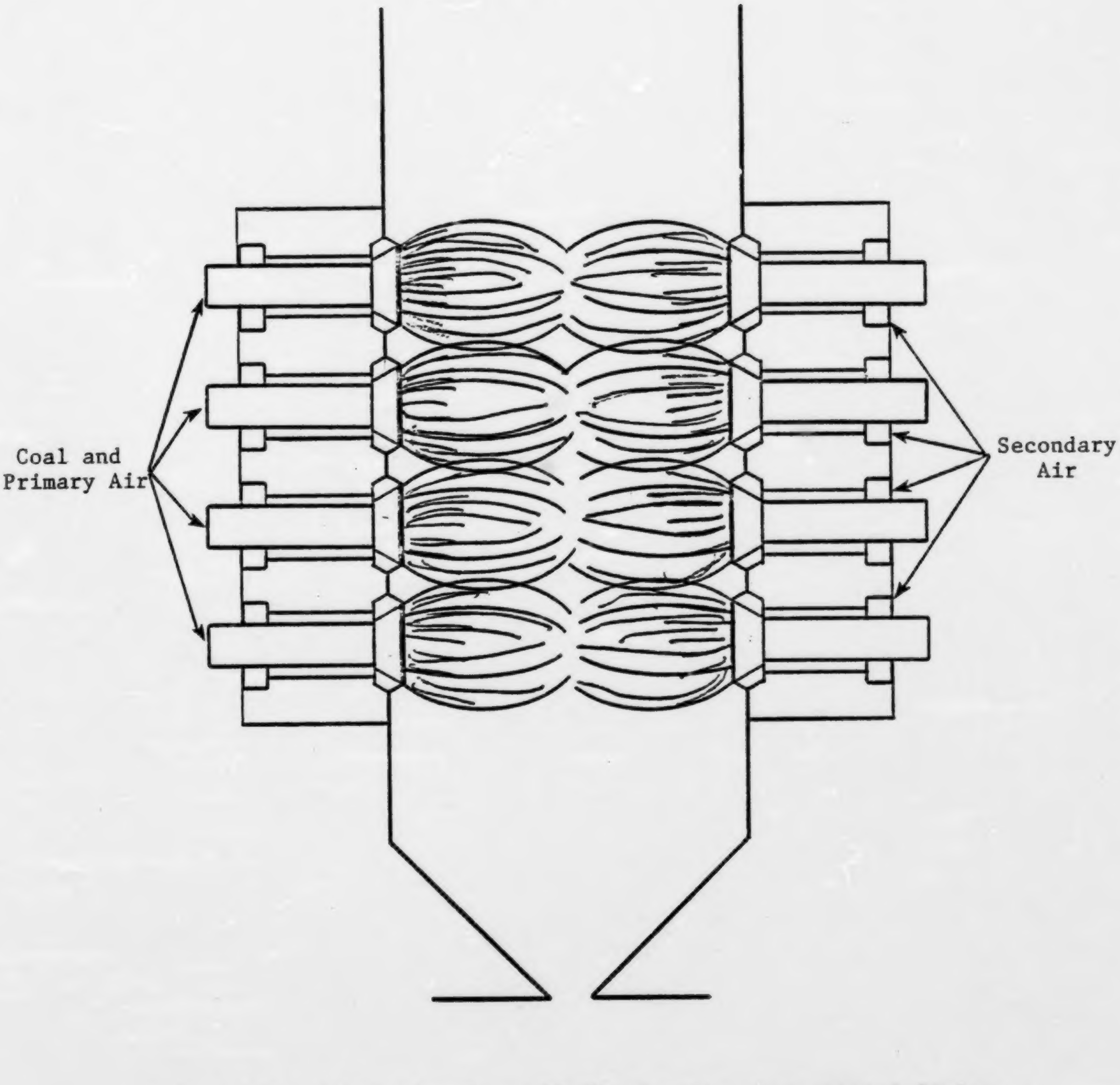
Coal and
Primary Air
Secondary
Air

Figure 8-3. Schematic of a wall fired unit using opposed firing.

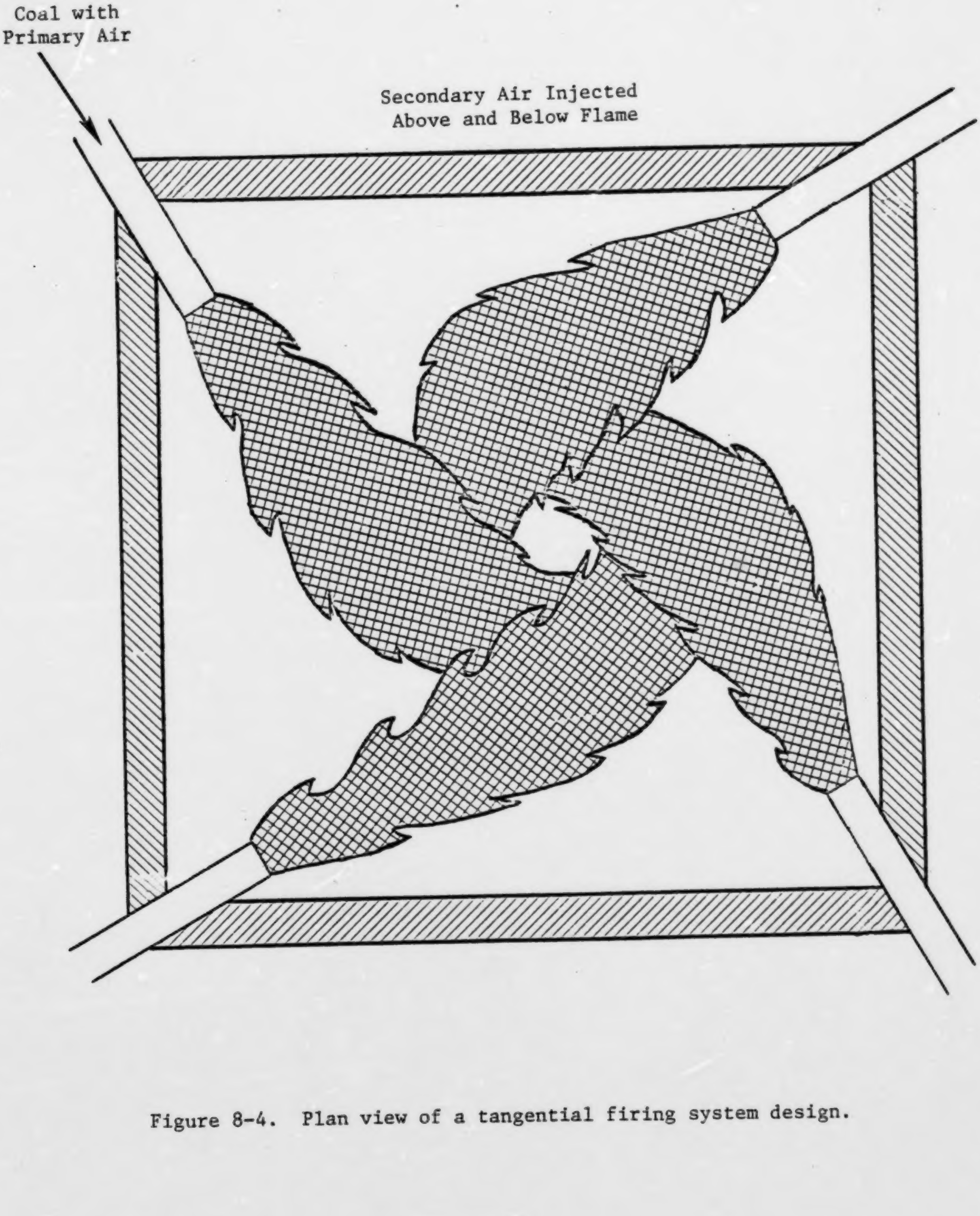
Coal with
Primary Air
Secondary Air Injected
Above and Below Flame

Figure 8-4. Plan view of a tangential firing system design.

at each burner level in the furnace. This firing system design naturally results in slower mixing of coal and combustion air and hence a slower combustion rate than the wall fired system design.

As with the wall firing designs, alterations have been made in recent years to tangential firing designs to further slow the combustion process and lower NO_x formation. These alterations have included diverting up to 20 percent of the combustion air to overfire air compartments located above the top burner level and moving the flame ignition point closer to the coal nozzles.

A tangential firing system design under development by EPA seeks to further slow the combustion process. The goal is to create a fuel rich fireball in the center of the furnace by diverting still more of the combustion air through tertiary air ports. These air ports are to be located in the same horizontal plane as the coal nozzles but directed at an angle closer to the furnace walls. A schematic of this design, called the fuel rich fireball, is presented in Chapter 4, Figure 4-2.

Another major difference in furnace design is in the method of ash collection. Units where the bottom ash is collected in a molten state are called wet bottom or slag tap units. Units where the bottom ash is collected in a solid rather than molten state are called dry bottom units.

The slag tap design is useful for coals that produce an ash that remains fluid at furnace temperatures. Ash collecting on the lower furnace walls drains down the walls and collects in a pool at the bottom of the unit. This pool of slag is tapped and drained at intervals or continuously. Keeping the ash in a fluid state is very critical in these designs, so small firing zones with high heat release rates are used to maintain high temperatures in the low regions of the furnace.

Slag tap units were quite popular in years past. About 33 percent of the B&W units sold between 1936 and 1969 larger than 140,000 kg/hr (300,000 lb/hr) steam were of the slag tap design.[5] However, most of the slag tap units designed after the mid 1950s were not really pulverized coal boilers. These units employed cyclone furnaces which burn crushed rather than pulverized coal.

All current designs of utility size pulverized coal units are dry bottom units.[6,7] With the increased emphasis on NO_x control in the early 1970s, boiler manufacturers ceased offering slag tap furnace designs. Also contributing to the increased use of dry bottom units were improvements in design which overcame difficulties in keeping the units free of ash and slag deposits. Additionally, dry bottom units have more flexibility to burn a variety of coals and to operate over wide load ranges.

With dry bottom units, the ash is cooled in suspension in the combustion gases. Ash striking the furnace walls or settling to the bottom of the unit is in a dry (nonmolten) state. Ash retained on the furnace walls is removed with sootblowers. At the bottom of the furnace is a water cooled hopper constructed by bending the lower ends of the front and rear wall tubes. The slope of the hopper is steeper than the angle of repose for ash. Thus, ash falling or settling to the bottom of the unit is automatically discharged through the opening at the bottom of the hopper.

Furnace Design Criteria

This subsection focuses on those aspects of furnace sizing necessary to evaluate the applicability of LIMB. Since slagging and fouling are major boiler system concerns, the impact of LIMB on these problems is also of major concern. Consequently, this subsection is heavily oriented toward furnace design as related to the control of slagging and fouling.

The most important step in design of a pulverized coal unit is proper sizing of the furnace. The furnace is the largest piece of equipment in the boiler system and its size directly influences the size and design of the associated equipment, structures, buildings, and foundations. The furnace must be large enough to provide adequate residence time for the combustion gases. Time is needed to complete burnout of the coal and to cool the combustion gases to the desired furnace exit gas temperature (FEGT). A related consideration is to make the dimensions large enough to prevent furnace wall slag accumulation in excess of that which can be removed with a reasonable amount of sootblowing.

The size of the upper furnace (the portion above the top row of burners) is determined by the desired FEGT. Proper selection of this temperature is critical. It must be high enough to achieve the desired steam temperatures in the superheater and reheater. Also it must be low enough to prevent slag accumulation (i.e. below the ash fusion temperature) or excessive fouling in the tightly spaced convection passes. The designs of the heat transfer components in the convection section are then dependent upon this temperature. As a practical matter, common design FEGTs range from about 1010 to 1245 °C (1850 to 2275°F).

Other important factors influencing furnace size are coal and ash properties. As discussed in Section 5, lower rank coals are considerably higher in moisture content and lower in heating value than higher rank coals. For equivalently rated units, the combustion of lower rank coals results in larger quantities of combustion gases than the combustion of higher rank coals. Thus, a unit designed for a lower rank coal would require a larger upper furnace volume to give a similar combustion gas residence time.

Ash properties also influence furnace size because of their contribution to slagging and fouling problems within the unit. Coals with low ash melting temperatures are more prone to slagging and require lower design FEGTs to prevent slag deposits in the convection section. Hence, larger furnace sizes are needed to achieve these lower FEGTs and also to prevent excessive slag accumulations on the furnace walls. Additionally, coals with high chloride contents or high ash sodium levels are more prone to causing fouling problems in the convection section. These coals also require lower FEGTs and larger furnace sizes than other coal types.

The residence time of combustion gases in the furnace is dependent upon the internal volume of the upper furnace. The upper furnace is the portion betweeen the upper row of coal nozzles and the furnace nose. The FEGT is dependent upon this residence time and on the area of radiant surface present in the upper furnace. Two furnace dimensions directly influencing upper furnace volume and radiant surface are the furnace plan area and the height from the top row of coal nozzles to the furnace nose. In order to decrease FEGT, boiler designers commonly increase these two dimensions.

Increasing these two dimensions also helps reduce slagging in the upper furnace by reducing the average gas temperatures and further removing the furnace wall surfaces from direct contact with combustion gases. In this manner, the chance for molten ash contact with furnace walls is reduced.

Design parameters such as heat release or liberation rates are commonly used by boiler manufacturers to develop adequate furnace dimensions. Heat release rates are expressed in terms of the quantity of heat released per unit time and divided by the furnace plan area, burner zone area, or furnace zone area. Heat liberation rates are actually volumetric heat release rates. They are commonly expressed in terms of the quantity of heat released per unit time and divided by the burner zone volume or furnace zone volume. Larger furnace sizes for a given heat input result in lower heat release or liberation rates.

Based on experience, boiler manufacturers specify lower heat release or liberation rates for fuels with higher slagging or fouling potential. Some ranges of design heat release rates reported by major boiler manufacturers for a variety of coals are presented in Table 8-2. Table 8-3 further shows the difference in furnace size with coal quality. These design values represent relatively recent practices and do not necessarily reflect earlier practices. As discussed later, current furnace designs are larger than 1960's designs for similar fuels.

Not all of the parameters mentioned above are used by all boiler designers and some of the parameters have little meaning for certain furnace types. For example, the furnace zone liberation rate usually has no impact on furnace size except for relatively small units between about 50 and 100 MW. Also, the burner zone heat release and liberation

TABLE 8-2. DESIGN PLAN AREA HEAT RELEASE RATES FOR A VARIETY OF COALS

Boiler Manufacturer	Plan Area Heat Release	
	J/sec-cm^2	10^6 Btu/hr-ft^2
Combustion Engineering[8]	440 - 630	1.4 - 2.0
Babcock and Wilcox[9]	460 - 600	1.45 - 1.9
Foster Wheeler[10,a]	540 - 630	1.7 - 2.0

[a] Value will be lower if the ash sodium content is above normal.

TABLE 8-3. RELATIVE FURNACE SIZE VERSUS COAL RANK FOR TANGENTIALLY FIRED BOILERS

Coal Type	Medium Volatile Bituminous	High Volatile Bituminous or Subbituminous	Low Sodium Lignite	Medium Sodium Lignite	High Sodium Lignite
Relative height from top coal nozzles to nose[a] (dimensionless)	1.0	1.15	1.17	1.52	2.1
Relative plan area[a] (dimensionless)	1.0	1.15	1.25	1.56	1.63
Plan area heat release rate[b]					
$J/sec\text{-}cm^2$	662	577	530	426	407
10^6 $Btu/hr\text{-}ft^2$	2.10	1.83	1.68	1.35	1.29

[a] These relative dimensions were reported by Combustion Engineering[11] and reflect example situations based on some specific coal properties and analyses. These dimensions also may vary for different coals of the same rank.

[b] These heat release rates were not reported by Combustion Engineering. Instead they are approximations based on the reported relative plan areas shown above and on the range of heat release rates shown in Table 8-2.

rates have little meaning in tangentially fired units because a significant portion of the fuel is combusted outside of the immediate burner zone. With wall fired units, however, the fuel is mostly consumed within this zone and these parameters are directly controllable by varying the spacing between burners.

In addition to adjustment of physical dimensions, other methods used to reduce temperatures to the convection section include flue gas tempering and increasing the available radiant surface.

Flue gas tempering is a process where cooled combustion gases from the convection section (commonly from a location just after the economizer) are reintroduced to the furnace near the furnace outlet. Dilution of the hot furnace gases with the cooled combustion gases serves to lower the FEGT. Since temperature reduction occurs near the furnace outlet, little reduction in furnace heat absorption occurs.

The heat absorption pattern through the convection section is altered by tempering. The initial heat absorption component, commonly the secondary superheater, usually absorbs less heat because of the lower combustion gas temperature. However, because of the increased combustion gas mass flow rate, components at the cooler end of the convection section absorb more heat. The net result is little change in total heat absorption or unit efficiency.

Additional radiant heat transfer surface can be provided by suspending widely spaced steam cooled panels or platens from the furnace roof. These devices consist of steam tubes lined up tangent to each other in widely spaced rows. Since the rows are parallel to the direction of gas flow, the principal means of heat transfer is radiation - not convection. Other methods include adding water cooled wing or curtain walls or water cooled division walls within the furnace.

Design of the lower furnace, although important, is not as critical as upper furnace design. One of the lower furnace design variables is the distance between the bottom set of coal nozzles and the point where the furnace walls bend to form the furnace hopper. This distance should be large enough to prevent slag accumulation on the lower front or rear walls and on the hopper slopes. Larger distances allow for more ash cooling before the ash contacts the furnace walls or hopper slopes. Larger distances also allow for the placement of wall sootblowers on the lower walls. The actual distance varies with the furnace width and depth and the fuel slagging potential. Practical values generally range from 3 to 9 m (10 to 30 ft).[12,13]

Other lower furnace design considerations include the angle of the hopper slopes and the opening of the hopper bottom. The slopes must be steeper than the angle of repose for ash so that collected ash is readily discharged from the hopper. The hopper bottom must be large enough to prevent hardened chunks of slag from plugging the opening. Openings are usually up to 1.2 m (4 ft) wide. Coals with a high slagging potential require openings close to this upper limit.[12,13]

In the burner zone the design must provide sufficient clearance to prevent flame impingement on the furnace wall tubes. Flame impingement causes strong localized reducing conditions aggravating slagging and tube corrosion. Recent burner designs developed to lower NO_x emissions slow the mixing of coal and air and increase flame length. Larger furnace dimensions are required to prevent flame impingement with these types of burners.

Ash Removal

During operation of a steam generating unit a portion of the coal ash is retained in the furnace, depositing on wall tube surfaces or settling to the bottom of the unit. If allowed to accumulate, the ash would cause furnace heat absorption to decrease and the exit gas temperature to increase, leading to plugging of the convection passes. Also, retained ash or slag on the furnace walls is highly corrosive leading to tube wastage. For these reasons, proper functioning of the furnace depends upon effective ash removal. Equipment used for this purpose include wall sootblowers and the bottom ash removal system.

Sootblowers operate by directing a jet of superheated steam or hot air tangent to the tube surfaces to dislodge accumulated ash and slag deposits. Another blower medium occasionally used to remove difficult slag deposits is water, which is sometimes more effective than steam or air. However, water impingement on the tube surfaces can cause localized temperature changes creating stresses that reduce tube life. Several rows of sootblowers are typically located along the upper furnace walls between the top level burners and the furnace arch. Another row is located on the lower furnace walls between the bottom level burners and the furnace hopper.

Wall sootblowers consist of short retractable nozzles operated individually on a timed basis. When a blower is in operation the nozzle projects a few cm (couple of inches) into the furnace and slowly rotates through a complete circle, cleaning a circular path about 1.5 m (5 ft) in radius. The actual size of the cleared path depends on the properties and amount of accumulated ash and slag. Since the cleaning radius can be considerably less than 1.5 m, sootblowers are spaced along the wall based on the expected cleaning radius. For sootblowers to be effective they must be operated before the slag accumulation becomes too great.

Once removed by the sootblowers, ash and slag deposits fall to the furnace bottom and through the opening in the hopper. Discharged ash is collected and removed with one of three basic types of ash removal systems. These systems remove ash either intermittently or continuously using hydraulic, pneumatic, or mechanical means.

With one system ash from the furnace hopper is collected and stored in a water filled hopper. The water-ash mixture is discharged intermittently through an outlet gate, passes through grinders to reduce oversized materials, and is hydraulically transported to disposal. A second system employs a refractory lined hopper, water cooled gates, grinders, and pneumatic or hydraulic transport. With a third design ash from the furnace is caught in a water filled trough. A scraper system continually moves the ash up a dewatering slope and dumps it onto belt conveyors which transport it to disposal. Further descriptions of these ash removal systems are provided in the literature.[14]

CONVECTION SECTION DESIGN AND OPERATION

This section discusses the principles of convection section design and operation needed to evaluate the applicability of LIMB. Design criteria for sizing and spacing system components are presented, and methods of removing retained ash and deposits are discussed.

Convection Section Design Criteria

The primary aim of convection section design is to size and arrange the system components for efficient and economical heat recovery. Important considerations include heat transfer, fouling, erosion, and corrosion.

The physical location of each of the heat transfer components is largely determined by heat transfer considerations though fouling considerations are also important. The superheaters and reheaters must produce high temperature steam - commonly about 540°C (1000°F), so they are located in the higher temperature regions of the convection section. The gas temperature in these regions may range from over 1090°C (2000°F) to about 650°C (1200°F).

Commonly, these components consist of several individual tube banks interspersed among each other. The combustion gases may thus pass by a series of tube banks, each a part of the superheater or reheater. Steam passes from tube banks located in cooler sections of the zone to tube banks in the hotter sections. The precise positioning of tube banks also depends on the slagging and fouling potential of the coal because slagging and fouling are related to flue gas temperatures.

The economizer is located further downstream in the convection section where the gas temperature ranges from about 650°C (1200°F) to about 315-430°C (600-800°F). The gas in this temperature range is too cool to provide efficient heating of the steam. Thus, the economizer is used as a device to preheat the much cooler boiler feedwater.

The air heater is located downstream of the economizer and further cools the combustion gases to about 150°C (300°F). This device serves to transfer residual heat from the combustion gases to the combustion air prior to its injection to the furnace.

Fouling considerations help determine the tube bank depths and individual tube spacings. Fouling and ash deposition on tube surfaces result in decreased heat transfer and can lead to ash bridging between tubes, effectively blocking gas passageways. In some high steam temperature units ash deposits can result in increased corrosion of tube surfaces. Therefore, maintaining relatively clean tubes is imperative.

Tight spacings between tubes and deep tube banks enhance convective heat transfer. However, they prevent sootblowers from penetrating and cleaning the entire tube bank. Thus, convection section design seeks to optimize tube spacings and tube bank depths to provide efficient heat transfer while maintaining sootblower effectiveness. Sootblower effectiveness is also related to the rate of ash deposition and the strength of the ash deposit. Both ash deposition and deposit strength increase with temperature. Thus, normal convection section design provides relatively wide tube spacings in the high gas temperature zones and tighter tube spacings in the cooler temperature zones where volumetric flow rates are lower and fouling less likely.

Table 8-4 presents data reported by Combustion Engineering for tube spacing as a function of flue gas temperature and coal quality. As shown in this table, very wide clearances and even platen surfaces are provided in the initial very high temperature zones where fouling conditions are most severe. Platens consist of tubes placed tangent to one another in rows parallel to the direction of gas flow. Platens are designed to provide little convective heat transfer. Instead they provide additional surface for radiant heat transfer to further cool the gases before they enter the tighter convective passes. Fouling coals require more platen surface than do nonfouling coals.

Another variable affecting convection pass design is erosion. Convective heat transfer is enhanced by high combustion gas velocities across the tube banks. However, high velocities also cause increased erosion of tube surfaces by entrained fly ash. This erosion is usually most severe in the economizer because of its tighter tube spacings. If severe, erosion can lead to premature tube failure. The oxides of silicon (SiO_2) and iron (Fe_2O_3) are the fly ash components most responsible for erosion. These components are found in greater quantities in bituminous type coals than in lower rank coals. To control erosion boiler manufacturers usually limit the maximum design velocity through the tube banks to between 14 and 20 m/sec (45 and 65 ft/sec) depending on the quantity of ash and its abrasive tendencies.[18,19]

A final major variable governing convection pass design is corrosion. The portion of the convection section most subject to corrosion is the air heater where condensation of sulfuric acid occurs on metal surfaces. This problem is most serious in units firing high sulfur coal. In some units designed in the past with steam temperatures of 565°C (1050°F) or higher, high temperature corrosion of the superheater and reheater tubes by molten ash deposits was also a problem. However, this problem is

TABLE 8-4. INFLUENCE OF COAL CHARACTERISTICS AND GAS TEMPERATURE ON CONVECTION PASS TUBE SPACINGS[a]

	Clearance Between Tubes	
Temperature Range °C (°F)	Fouling Coal cm (in.)	Nonfouling Coal cm (in.)
1320–1090 (2400–2000)	Platen - 56 (22)	Platen - 56 (22)
1090–950 (2000–1750)	Platen - 30 (12)	Spaced - 18 (7)
950–790 (1750–1450)	Spaced - 15 (6)	Spaced - 7.6 (3)
790–650 (1450–1200)	Spaced - 7.6 (3)	Spaced - 5.1 (2)
650–430 (1200–800)	Bare Tube Economizer	Finned Tube Economizer

[a] Information reported by Combustion Engineering in various literature sources.[15,16,17]

largely nonexistant among the lower steam temperature units prevalent today.

Sulfuric acid is formed by the combination of SO_3 and H_2O in the flue gas. Because of equilibrium considerations, only a small amount of SO_3 is required to condense with water from the flue gas and form a concentrated acid solution. The dewpoint where acid begins to condense from the flue gas is considerably higher than the point where moisture alone would begin to condense. A typical acid dewpoint for a high sulfur coal fired boiler is around 150°C (300°F).

When the gas temperature falls below the dewpoint an acid mist begins to form on available surfaces. However, even with gas temperatures above the dewpoint, condensation can occur on cool surfaces such as the cold end of the air heater. Methods of reducing cold end corrosion include control of the exit flue gas temperature and entering air temperature to sufficiently high levels to minimize condensation.

Ash Removal

During operation of a steam generating unit a portion of the entrained coal fly ash is retained in the convection section depositing on or fouling tube surfaces. Also, a portion of the ash settles into hoppers associated with the economizer and air heater - locations where the combustion gases are forced to undergo a change of direction. Ash retained in the convection section will reduce heat transfer and can lead to blockage of gas passageways. Therefore, proper functioning of the convection section depends upon effective removal of retained ash. Equipment used for this purpose include long retractable sootblowers and ash removal systems associated with the economizer and air heater ash hoppers.

Long retractable sootblowers are used to clean superheater, reheater, and economizer tube surfaces. These devices are spaced throughout the convection section and are designed to penetrate the cavities between the various tube banks. When operated, each sootblower penetrates its respective cavity, rotating nozzles which direct jets of superheated steam or hot air at the tube surfaces. Sootblowers are often designed to operate automatically or with manual override capability. The effective cleaning radius of each sootblower is about 1.2 to 2.7 m (4 to 9 ft) depending on the gas temperature and ash characteristics.[20] To be effective the sootblowers must be operated often enough to prevent deposits from accumulating and sintering to great strength. Sootblowers and other types of washing equipment are also used to keep air heater surfaces clean.

Ash removal systems are used to remove ash collecting in the economizer and air heater ash hoppers. The hoppers are usually designed to discharge ash continuously to a receiving vessel. Ash is conveyed intermittently or continuously using hydraulic, pneumatic, or mechanical means. Systems designed for bituminous coals often receive the economizer ash in water filled tanks which are flushed intermittently. However, this method is not practical for high calcium containing lignitic or subbituminous coals. The cementitious nature of the fly ash from these coals makes dry removal preferable.

SLAGGING AND FOULING CONTROL

Control of slagging and fouling relates back to understanding the mechanisms by which they occur. Slagging results from contact of molten or semi-molten ash particles with tube surfaces. When these particles contact the cooler tube surfaces they are solidified. The strength of attachment of the particles to the surface is influenced by the temperature of the surface and the particle melting characteristics. A discussion of the influence of ash composition on melting characteristics was presented previously in Section 5.

Often slag deposits occur after a conditioning period. Gray and Moore[21] suggest the following mechanism. When molten ash particles contact the tube surfaces they solidify and fracture. Most of the particle is reentrained in the combustion gases but a small residue remains on the tube. After many such bombardments a base deposit forms on the tube. This deposit serves to insulate the cooler tube surface from the hot combustion gases and from the bombarding ash particles. The temperature of the deposit outer surface increases causing the deposit growth rate to accelerate. Eventually the deposit becomes heavy enough that it falls from the tube or it becomes molten and runs down the furnace wall.

Fouling occurs by another mechanism. As the combustion gases enter the convection section and are cooled, volatile ash constituents condense on entrained ash particles and available tube surfaces. Ash particles conditioned in this manner strike the tube surfaces and are retained. A deposit grows and becomes bonded through chemical reactions between the various particles and ash constituents. Gray and Moore[21] explain that two important factors affecting fouling are the rate of deposition and the deposit strength. The first factor is related to temperature and the quantities of ash and volatile ash constituents present in the coal. The latter is related to the chemical composition of the deposit, temperature, and time. A discussion of the influence of ash composition on the coal fouling potential was also presented in Section 5.

In control of slagging the most important design consideration is proper furnace sizing. The furnace should be sized within practical constraints to minimize molten ash deposition on the furnace walls. Sootblowers are then designed to control the slag deposits that inevitably form. In general, the furnace should be sized large enough to (1) minimize ash contact with the walls and (2) provide sufficient radiant surface to rapidly cool the combustion gases and ash particles below the ash fusion temperatures.

Major design factors related to control of fouling again include proper furnace sizing as well as proper spacing and arrangement of tube banks and sootblowers. Proper furnace sizing is primarily important through its impact on flue gas temperature to the convection section. High gas temperatures increase the fouling rate and risk carryover of molten ash particles into the convection passes. Furnace design sometimes includes the use of the flue gas tempering to control flue gas temperatures with smaller furnace size. Proper spacing and arrangement of tube banks and sootblowers are important for controlling deposits that do occur. Wider spacings are needed between tubes in the hotter portions of the convection section where the deposition rate is highest.

Some operating factors affecting slagging and fouling include adjustments in boiler load, excess air, and pulverized coal size, and use of coal additives.

Reducing boiler load has the same impacts on slagging and fouling as increasing furnace size. Effectively, when load is reduced, a larger furnace and more radiant surface are provided per quantity of coal fired. This operating procedure minimizes slagging in the furnace and reduces furnace exit gas temperatures. Thus, fouling in the convection section is also lowered.

Increasing excess air minimizes the occurrence of reducing conditions within the furnace. As discussed in Section 5, ash fusion temperatures are increased under oxidizing conditions especially for bituminous coals with a high iron content. Thus, increasing excess air tends to reduce slagging in the furnace. Convection pass fouling has also been linked to low excess air rates. Fouling was found to increase[22] for low rank coals as excess air was reduced below design levels.

Slagging and fouling are also affected by the pulverized coal size. As the particle size increases the more reducing is the combustion environment immediately surrounding the particle. Reducing conditions lower ash fusion temperatures thereby increasing the slagging and fouling potential. A common design pulverized coal size for bituminous coals is 70 percent through 200 mesh. However, low rank coals are sometimes allowed larger particle sizes because of their higher reactivity and lower grindability. Fouling has been found to decrease for these coals as the coal size is[22] reduced from less than 40 percent to over 70 percent through 200 mesh.[22]

Another factor affecting coal slagging and fouling is the use of coal additives. The use of additives in utility boilers has been aimed primarily at reducing slag viscosity in slag tap units. In various utility tests limestone[23] has been added at rates of about 2 to 10 percent of the coal feed rate.[23] Other compounds containing boron have also been tried. As discussed in Section 5, increasing the base content of a high acid coal tends to lower the ash fusion temperatures and also the slag viscosity. For a high base coal, the opposite result occurs.

Increasing slagging in a dry bottom pulverized coal unit could be useful in situations where slagging is much lower in the furnace than the unit was designed for. In these cases, too much heat is absorbed from the combustion gases in the furnace thereby causing a reduction in heat transfer in the convection section. The result is reduced steam superheat temperatures. Thus, increasing furnace slagging would reduce furnace heat absorption and increase steam temperatures.

There is evidence that various alkaline earth compounds, including those containing calcium or magnesium, could be useful for modifying the surface properties of fly ash particles to reduce fouling. Some pilot and full scale tests carried out by DOE[24] indicated that limestone addition was effective at reducing the fouling deposit strength for units burning high fouling North Dakota lignite. However, other than a few tests, additives are not yet being used on a practical scale to control fouling.[25]

DESIGN PROFILE OF THE EXISTING BOILER POPULATION

The usefulness of LIMB as a retrofit technology depends on the design features prevalent in the existing boiler population. This section profiles some of the major design features including:

- boiler use categories,
- coal types fired,
- unit capacities,
- furnace types, and
- historical furnace size.

Boiler Use Categories

The design features of pulverized coal boilers are determined by the end use of the product steam. Electric utilities are primarily interested in using steam to generate electricity. Boilers operated by utilities are generally very large and produce high temperature/high pressure steam. These units come fully equipped with superheaters, reheaters, economizers, and air heaters.

Although the industrial/commercial sector sometimes uses steam to generate electricity, the desired use is often for process steam or space heating. Industrial boilers are usually smaller and produce lower temperature/pressure steam than utility units. Industrial/commercial boilers sometimes lack superheaters, almost never have reheaters, and frequently lack an economizer or air heater. As indicated by Table 8-5, very little of the total pulverized coal boiler capacity in the U. S. is represented by industrial/commercial units. Almost all of this capacity occurs in electric utility units.

TABLE 8-5. COAL CONSUMPTION BY END USE SECTOR, 1975

End Use Sector	Coal Consumed	
	Mg/yr	10^6 tons/yr
Industrial/Commercial Boilers[a]		
Pulverized Coal	10.2	11.2
Total	40.3	44.4
Electric Utilities[b]	368.3	406.0
National Total[b]	510.4	562.6

[a] Estimates made by Pedco.[26]

[b] Total coal consumption reported by DOE.[27]

Coal Types Fired

The distribution of coal types fired in utility boilers is presented in Table 8-6. This table shows that in 1978 about 75 percent of the coal consumed in utility boilers was bituminous coal, 18 percent was subbituminous, and 7 percent was lignite. These numbers are probably indicative of the proportion of national coal fired boiler capacity designed for each fuel type. If this assumption is true, this table further implies that about 90 percent of the 1978 subbituminous coal and lignite consumption resulted from units that came on line during the 1970s.

This conclusion is supported by Combustion Engineering (CE) sales data which show that most CE subbituminous and lignite units were designed after 1970.[30,31] In fact, none of the lignite units were designed prior to 1966. Of six subbituminous units designed prior to 1966, five had a capacity of 200 MW or less.

Unit Capacities

Utility pulverized coal units in the U. S. range in size from less than 100 MW to about 1300 MW capacity. Older units tend to be smaller in capacity than newer units. The average size of units designed by CE in the 1960 to 1965 time frame was 380 MW. The average unit size since that time has held relatively constant at 575 MW.[30,31] The trend toward increasing size is also evident for units burning lower rank coals. As mentioned above, the earliest subbituminous coal units were fairly small. However, the sizes of subbituminous and lignite units designed since 1966 are roughly comparable to the sizes of bituminous coal units.

Furnace Types

Another important design feature of the existing boiler population is furnace type. Information concerning furnace types prevalent in the existing population was presented earlier in Section 8. A summary of that discussion follows.

Almost all pulverized coal fired boilers in the U. S. use tangentially fired or wall fired furnaces. Arch fired furnaces are only used to combust fuels difficult to ignite, such as anthracite. Among the wall fired designs, a majority of the units less than 300 MW in capacity incorporate one wall firing. The larger units exclusively use opposed firing.

All utility size pulverized coal units in the U. S. designed since the early 1970s are dry bottom units. A significant number of units designed before 1970 incorporate slag tap bottom ash removal. Babcock and Wilcox reports that about 33 percent of the total steam capacity of their larger units sold between 1936 and 1969 was of the slag tap design. However, those designed after the mid 1950s were principally cyclone units which utilize crushed rather than pulverized coal.

TABLE 8-6. DISTRIBUTION OF COAL TYPES CONSUMED IN UTILITY STEAM-ELECTRIC PLANTS, 1969 and 1978[a]

Year	Gross Heating Value kJ/kg (Btu/lb)	Number of Plants	Percent of Total	Coal Consumption		Percent of Total
				Mg/yr	10^6 tons/yr	
1969	Above 23,200[b] (10,000)	407	94.2	263.4	290.3	95.4
	18,600-23,200[c] (8,000-10,000)	15	3.5	7.7	8.5	2.8
	Below 18,600[d] (8,000)	10	2.3	4.9	5.4	1.8
	Total	432	100.0	276.0	304.2	100.0
1978	Above 23,200[b] (10,000)	310	81.6	324.1	357.3	74.5
	18,600-23,200[c] (8,000-10,000)	56	14.7	78.8	86.9	18.1
	Below 18,600[d] (8,000)	14	3.7	32.0	35.3	7.4
	Total	380	100.0	435.0	479.5	100.0

[a] Figures were compiled from data reported by the National Coal Association in references 28 and 29. The data cover power plants greater than 25 MW in capacity.

[b] Representative of bituminous coals.

[c] Representative of subbituminous coals.

[d] Representative of lignite coals.

Historical Furnace Size

The existing boiler population reflects changes in design furnace sizes over the years as a result of changing coal quality and improved capabilities among the major boiler manufacturers. In general, furnaces are considerably larger now than they were in the 1960s.

In past years boilers were principally designed to fire relatively high quality bituminous coals which do not need as large a furnace size as lower quality, lower rank coals. In addition, the capabilities of boiler manufacturers to design and construct large furnaces were more limited than today. For example, CE reports that their single furnace capability increased from about 325 MW in the early 1960s to over 600 MW in the early 1970s and specifically details how maximum furnace widths evolved over this time frame.[30,31] The larger boilers designed during this period incorporated multiple firing cells through the use of centerwalls within the furnace.

Because of the greater economy in recovering heat in the convection section rather than in the furnace, heat release rates were maintained at rather high levels in the 1960s. However, in the late 1960s the declining quality of existing coal supplies and the increased use of lower quality fuels made reliability an important issue. Thus, design heat release rates were lowered which meant increased furnace size. Also, in recent years lower heat release rates have been used to help reduce NO_x emissions. Figure 8-5 illustrates how design burner zone heat release rates have changed for Babcock and Wilcox over the past 20 years. Similarly, Table 8-7 shows the change in furnace design philosophy for Combustion Engineering over the same time period.

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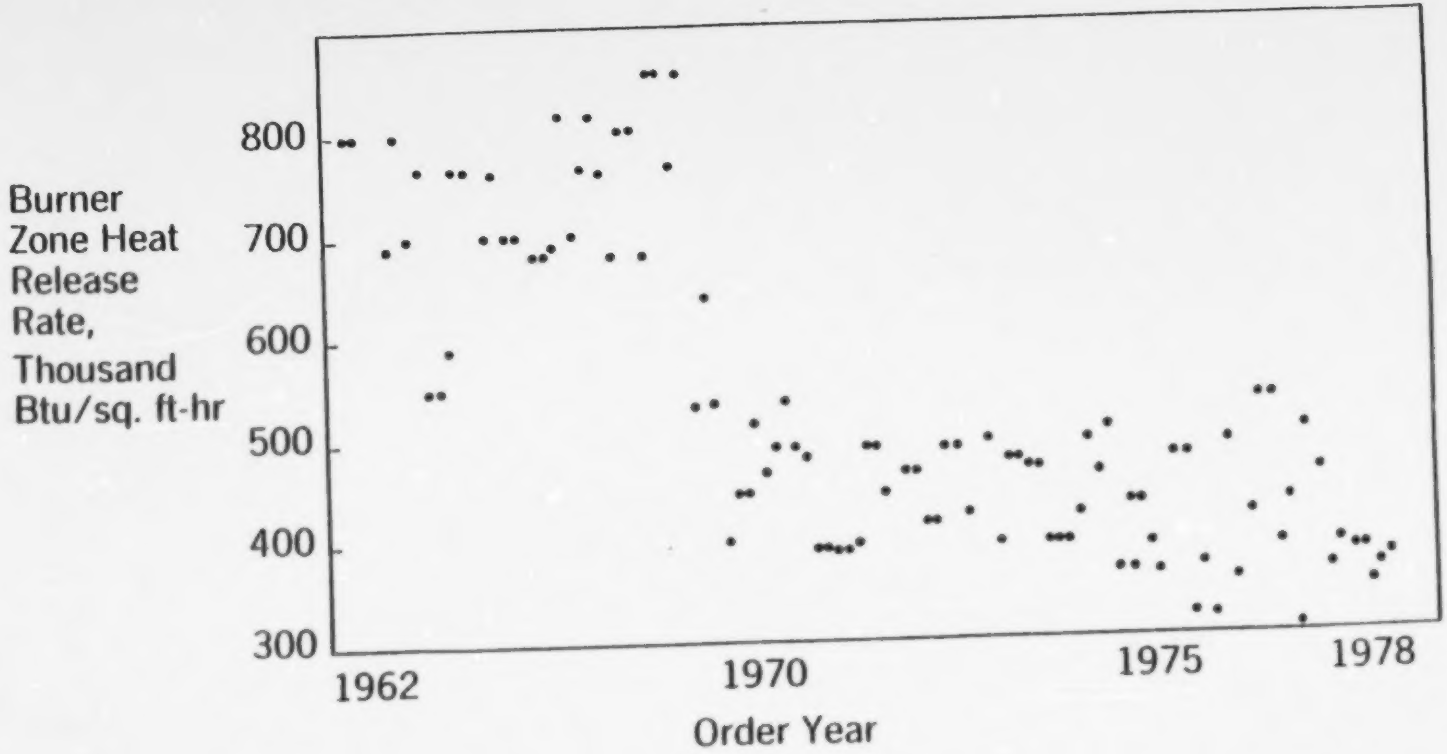

Figure 8-5. Change in burner zone heat release rate with time for units designed by Babcock and Wilcox.[32]

TABLE 8-7. CHANGES IN DESIGN FURNACE SIZE WITH TIME FOR UNITS DESIGNED BY COMBUSTION ENGINEERING[a]

Unit	Plan Area	EPRS[b]	Volume
900 MW/Eastern Bituminous Coal/ 1978 vs. 1963	11% larger	14% larger	18% larger
600 MW/Midwestern Bituminous Coal/ 1978 vs. 1966	15% larger	10% larger	22% larger
500 MW/Montana Subbituminous Coal/ 1978 vs. 1970	18% larger	15% larger	28% larger

[a] This information was presented in reference 30 and represents CE's change in design philosophy for three specific sets of design conditions.

[b] Effective projected radiant surface.

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SECTION 9

BOILER INJECTION IMPACTS

This section primarily discusses boiler system impacts associated with the application of LIMB technology to pulverized coal boilers. Also, some general observations on the influence of boiler design on the emission control perfromance of LIMB are presented.

IMPACTS OF LIMB ON BOILER OPERATION

The applicability of LIMB as a retrofit technology for pulverized coal fired boilers depends on its effect on boiler operation. If major design modifications or severe boiler operating impairments are required to apply LIMB, then its usefulness in retrofit situations is reduced. This subsection assesses the impacts of LIMB on boiler operation. These include material and energy balance impacts and boiler operation impacts in the furnace and convection sections.

Material and Energy Balance Impacts

The normal solids loading in a boiler system consists of the ash resulting from coal combustion. With limestone injection, this solids loading is greatly increased by the added limestone solids and resulting sulfur reaction products. In the process a small but significant thermal efficiency loss is exacted on the boiler system. In this subsection, these impacts are described and compared for some example situations.

The amount of limestone injected into the furnace is proportional to the coal sulfur content and to the desired Ca/S molar ratio. The injected material directly increases the boiler solids loading, but by an amount less than the original mass of raw limestone. Limestone mass reduction occurs in two steps. First, most of the moisture is evaporated during the limestone grinding/pulverizing process. Next, furnace injection causes evaporation of the remaining moisture and flash calcination of the limestone solids. This latter step consists of decomposition of calcium and magnesium carbonates to the oxides through CO_2 evolution as shown in the following reaction.

$$CaCO_{3(s)} \longrightarrow CaO_{(s)} + CO_{2(g)} \qquad (9\text{-}1)$$

Available kinetic and experimental data[1,2] indicate that the calcination reaction may not go to completion in the short furnace residence times available (commonly about two seconds or less). The extent of the calcination reaction is governed by furnace conditions and depends primarily on the time-temperature history of the limestone particles.

Conceivably, as little as 75 percent of the injected limestone is converted to the oxides though 90 percent conversion appears more likely.

Although calcination does not appear to be the rate limiting step,[2] a large reduction in calcination percentage is undesirable primarily because it reduces the availability of CaO for sulfur capture. However, reduced calcination also increases the mass of limestone solids thus imposing a larger impact on the boiler solids loading. Table 9-1 presents a representative limestone analysis and shows the impact of calcination on the limestone mass. As shown, reducing the degree of calcination from 100 to 75 percent increases the mass of limestone solids by about 20 percent.

The formation of sulfur reaction products also increases the boiler solids loading. Classically, the predominant sulfur products formed under oxidizing conditions are calcium sulfate and calcium sulfite which result from the following generalized reactions:

$$\mathrm{CaO}_{(s)} + \mathrm{SO}_{2(g)} \longrightarrow \mathrm{CaSO}_{3(s)} \qquad (9\text{-}2)$$

or

$$\mathrm{CaO}_{(s)} + \mathrm{SO}_{2(g)} + \tfrac{1}{2}\mathrm{O}_{2(g)} \longrightarrow \mathrm{CaSO}_{4(s)} \qquad (9\text{-}3)$$

Another potential reducing zone sulfur capture mechanism which might occur with LIMB includes direct reaction between limestone particles (before calcination occurs) and H_2S as follows:

$$\mathrm{CaCO}_{3(s)} + \mathrm{H}_2\mathrm{S}_{(g)} \longrightarrow \mathrm{CaS}_{(s)} + \mathrm{H}_2\mathrm{O}_{(g)} + \mathrm{CO}_{2(g)} \qquad (9\text{-}4)$$

Other mechanisms are also possible. In any case, gas phase reactants are combined with a solid phase reactant to produce a solid phase product of greater weight than the calcined limestone solid.

The overall boiler solids loading impact associated with LIMB is thus related to several factors. The most important factor is the quantity of limestone injected which in turn is related to the coal sulfur content and the desired Ca/S ratio. The loading is further affected by the extents of limestone calcination, sulfur capture, and oxidation to produce the sulfate. And since the initial boiler solids loading is dependent on the coal ash content, the relative impact of LIMB is directly related to the coal sulfur to ash (S/A) ratio.

Table 9-2 presents a set of generalized expressions for calculating the boiler solids loadings for any given coal sulfur and ash level. Some specific calculated solids impacts are presented in Table 9-3 for a bituminous, high sulfur, high ash coal and a subbituminous, low sulfur, medium ash coal. The results show that the boiler solids loading more than doubles with limestone injection for a high sulfur coal and a Ca/S ratio of two. Even for a low sulfur coal, the solids loading is shown

TABLE 9-1. REPRESENTATIVE LIMESTONE ANALYSIS AND IMPACT OF CALCINATION

Raw Limestone

Analysis, wt. %	Dry Basis	Wet Basis
$CaCO_3$	94.0	84.6
$MgCO_3$	2.0	1.8
inerts[a]	4.0	3.6
H_2O	-	10.0

Limestone After Calcination

Analysis, wt. % of original wet limestone	75% Calcination	100% Calcination
CaO	35.6	47.4
MgO	0.6	0.9
inerts	3.6	3.6
$CaCO_3$	21.2	-
$MgCO_3$	0.5	-
total solids	61.5	51.9

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[a] A representative inerts analysis expressed as a percentage of dry limestone is as follows:

SiO_2 = 2.0%
Al_2O = 1.5%
Fe_2O_3 = 0.5%
Total - 4.0%

TABLE 9-2. GENERALIZED EXPRESSIONS FOR BOILER SOLIDS LOADING WITH LIMESTONE INJECTION

	Boiler Solids Handling Requirements - lb/ton coal[a,b]			
	Ca/S molar ratio = 2		Ca/S molar ratio = 4	
Degree of Calcination =	100%	75%	100%	75%
Raw limestone addition to boiler	147.8S	147.8S	295.5S	295.5S
Limestone solids remaining after calcination	76.9S	90.9S	153.7S	181.7S
Increased solids weight due to[c] $CaSO_4$ formation (50% S capture)	25.0S	25.0S	25.0S	25.0S
Ash resulting from coal combustion	20.0A	20.0A	20.0A	20.0A
Total boiler solids loading	20A + 101.9S	20A + 115.9S	20A + 178.7S	20A + 206.7S
Percent increase in boiler solids loading	509.5 S/A	579.5 S/A	893.5 S/A	1034 S/A

[a] Multiply expressions by 0.5 to obtain kg/Mg coal.

[b] S = percent sulfur in coal on an as-fired basis.
A = percent ash in coal on an as-fired basis.

[c] These expressions represent the increased weight of $CaSO_4$ over that of the CaO from which it is formed. All of the captured S is assumed to be converted to $CaSO_4$.

TABLE 9-3. COMPARATIVE BOILER SOLIDS LOADING IMPACTS FOR HIGH AND LOW SULFUR COALS

	Boiler Solids Loading - lb/ton coal[a]			
	Illinois Bituminous 4.0% Sulfur 16.0% Ash Ca/S=2		Montana Subbituminous 0.6% Sulfur 9.0% Ash Ca/S=4	
Degree of Calcination =	100%	75%	100%	75%
Raw limestone addition to boiler	591.2	591.2	177.3	177.3
Limestone solids after calcination	307.6	363.6	92.2	109.0
Increased solids weight due to $CaSO_4$ formation (50% S capture)[b]	100.0	100.0	15.0	15.0
Ash resulting from coal combustion	320.0	320.0	180.0	180.0
Total boiler solids loading	727.6	783.6	287.2	304.0
Percent increase in boiler solids loading	127%	145%	59.6%	68.9%

[a] Multiply numbers by 0.5 to obtain kg/Mg coal.

[b] These numbers represent the increased weight of $CaSO_4$ over that of the CaO from which it is formed. All of the captured S is assumed to be converted to $CaSO_4$.

to increase by over 50 percent. This presumes that an increased Ca/S ratio of four is needed to achieve the desired sulfur capture with the low sulfur coal.

Limestone injection also results in a net loss in boiler thermal efficiency. Some of the heat produced by coal combustion is required to heat the limestone above ambient temperature (including evaporation of contained moisture) and to drive the endothermic calcination reaction. Some heat is in turn supplied by the exothermic sulfation reaction but the overall result is a net thermal energy loss. This thermal loss is in addition to the electrical energy requirements for grinding and conveying limestone. Both types of losses require increased boiler coal consumption to maintain the plant power output.

The overall boiler heat impact associated with limestone injection is a state function subject only to the inlet and outlet conditions of the reactants and products. These impacts are independent of the intervening temperature extremes in the furnace and of the heat effects of any intermediate reactions that may occur. A generalized set of expressions for calculating boiler thermal losses as a function of the quantity of limestone injected is presented in Table 9-4.

This table separates the boiler heat effects into three distinct categories and quantifies the effects as functions of the amount of limestone injected. The first category is the heat involved in raising the limestone temperature from ambient conditions to the temperature of the flue gas exiting the air heater. This category includes evaporation of moisture contained in the limestone. For simplicity, all of this heating is associated with the boiler, although it primarily occurs in the limestone feed system and sometimes sources other than the boiler provide a portion of the required heat. For a given set of ambient and flue gas conditions this heat requirement is dependent only on the amount of limestone injected.

The second category is the heat required to drive the endothermic calcination reaction at the flue gas temperature exiting the air heater. This heat requirement is dependent on the amount of limestone which undergoes calcination. The third category is the heat recovered in the exothermic sulfation reaction at the flue gas temperature exiting the air heater. This heat credit is dependent on the amount of limestone used to produce the calcium-sulfur reaction products.

None of these categories is strictly meaningful taken alone. For example, the calcination and sulfation reactions do not take place at the temperature exiting the air heater; instead they occur at much higher temperatures in the furnace and initial portions of the convection section. However, the total system heat impact is a state function independent of the series of steps chosen to represent it.

TABLE 9-4. GENERALIZED BOILER SYSTEM HEAT REQUIREMENTS RESULTING FROM LIMESTONE INJECTION[a,b]

	Heat Requirement	
	J/g limestone	Btu/lb limestone
Heating of limestone[c] 27°C - 149°C 80°F - 300°F	364.9	156.9
Calcination reaction at 149°C (300°F) $CaCO_3 \longrightarrow CaO + CO_2$	$529F_c$	$657.6F_c$
Sulfation reaction at 149°C (300°F)[d] $CaO + SO_2 + \frac{1}{2}O_2 \longrightarrow CaSO_4$	$-4360F_u$	$-1875F_u$

[a] None of these categories is strictly meaningful taken alone, but combined they portray the overall system heat effect which is a state function.

[b] F_c = fraction of raw limestone calcined in boiler.
F_u = fraction of limestone utilized to capture SO_2.

[c] Includes moisture evaporation.

[d] All of the captured sulfur is assumed to be converted to $CaSO_4$.

Table 9-5 compares some example boiler thermal effects for a high sulfur bituminous coal and a low sulfur subbituminous coal. As expected, the thermal effects are more significant for the high sulfur coal case; coal consumption requirements are increased by up to 1.0 percent. For the low sulfur case coal consumption requirements are increased by up to 0.6 percent. For a given limestone injection rate the most important factors affecting the heat requirements are the calcination and sulfation reactions. Although reductions in the degree of limestone calcination are not desired, they do result in decreased boiler thermal losses. However, decreases in the degree of sulfur capture directly reduce the heat credit associated with this reaction thus increasing the boiler net thermal losses.

Furnace Operation Impacts

Furnace operation impacts associated with LIMB may result from both operation of the low NO_x burners and limestone injection. The primary areas of concern are the potential impacts on combustion/heat transfer, slagging, and bottom ash removal.

Combustion/Heat Transfer--

Two key areas of concern with retrofit of low NO_x burners on existing units are the increased combustion zone requirements of these burner designs and their impact on the heat transfer profile throughout the boiler system. These concerns are in addition to any physical constraints related to installation of the burners and associated tertiary air ports.

As discussed earlier in this section, a key aspect of low NO_x burner design is slowing the mixing rate of coal and combustion air thereby slowing the combustion process. The results are increased flame lengths and combustion residence time requirements as compared to other burners with similar coal combustion capacities. If the furnace is not large enough, flame impingement on the furnace walls could result leading to increased slagging and excessive corrosion of the wall tubes. Also, an insufficient furnace size may not provide enough residence time to complete the combustion process thereby impairing fuel efficiency.

Obviously, a new unit could be designed to avoid these problems. However, in an existing unit the only solution may be to derate the boiler. The existing units most likely to incur these problems are those with the highest furnace heat release rates; in other words, those units with the smallest furnace size per quantity of coal fired. The existing units best fitting this description are those designed for high rank coals with low slagging and fouling potentials - especially those units designed during the 1960s. These units represent a substantial portion of the potential retrofit market.

TABLE 9-5. BOILER SYSTEM HEAT REQUIREMENTS FOR HIGH AND LOW SULFUR COALS[a]

	Illinois Bituminous 4.0% sulfur 10,100 Btu/lb coal 20.20 x 10^6 Btu/ton coal Ca/S=2 50% sulfur capture		Montana Subbituminous 0.6% sulfur 8,570 Btu/lb coal 17.14 x 10^6 Btu/ton coal Ca/S=4 50% sulfur capture	
Degree of Calcination =	100%	75%	100%	75%
Raw limestone addition to boiler - lb/ton coal	591.2	591.2	177.3	177.3
Heat consumption - Btu/ton coal[b]				
heating limestone	92,760	92,760	27,820	27,820
calcination reaction	388,800	291,600	116,600	87,440
sulfation reaction[c]	-277,100	-277,100	-41,550	-41,550
total	204,500	107,300	102,900	73,710
Deration of coal heating value	1.01%	0.531%	0.599%	0.430%
Increased coal consumption to maintain boiler load	1.02%	0.534%	0.603%	0.432%

[a] Following are some metric conversion factors:
J/g = Btu/lb x 2.325; J/Mg = Btu/ton x 1163; kg/Mg = lb/ton x 0.5.

[b] None of these categories is strictly meaningful taken alone but combined they represent the overall system heat effect which is a state function.

[c] All of the captured S is assumed to be converted to $CaSO_4$.

Another important area of concern related to retrofit of low NO_x burners is their impact on the heat absorption profile through the unit. Low NO_x burners reduce peak flame temperatures and slow the combustion rate both of which could have some effect on radiant heat transfer in the furnace. A decrease in furnace heat absorption could lead to increased slagging and fouling of the convection section. On the other hand, increased furnace heat absorption could lead to lowering of steam temperatures below their design levels. The latter situation may especially be a problem in units that are derated because of the low NO_x burners. Reducing boiler load tends to cause an increase in furnace heat absorption.

Common operating procedures to control furnace heat absorption include burner tilt for tangentially fired units and flue gas recirculation. Furnace heat absorption is decreased by tilting the burners up or by increasing flue gas recirculation. An experimental method of controlling furnace heat absorption is to influence the degree of slagging by the use of coal additives. However, it is doubtful that it would be practical to use any additive in addition to the limestone already used with LIMB. Other more drastic measures of influencing furnace heat absorption include unit modifications such as covering some of the tube surface with refractory (decreases heat absorption) or installing extra radiant surface (increases it). Another common operating procedure to control furnace exit gas temperatures, aside from influencing furnace heat absorption, is flue gas tempering.

Use of any of the common operating procedures discussed above may prove adequate for dealing with altered boiler system heat transfer profiles. However, their use will have to be considered in conjunction with their impact on other operating factors. One such factor is flue gas velocity through the convection section, which affects erosion. Also, since these procedures are commonly used to allow boiler load changes, their use with low NO_x burners may limit the boiler system load change flexibility.

Other potential combustion related problems specifically related to limestone injection include flame stability and combustion air control. Injection of large quantities of limestone directly mixed with the fuel raises the possibility of flame stability problems. Also, pneumatic injection of large quantities of limestone, whether with the fuel or separately, may cause problems in controlling the rate of combustion air to the furnace - especially over varying boiler loads.

Slagging--

LIMB may affect slagging in the furnace in two ways. First, the reduced flame temperatures may reduce the formation of molten ash particles during combustion. And second, the limestone particles may interact with the ash thereby altering ash fusion temperatures and hence its slagging potential.

Normal peak flame temperatures in a utility boiler furnace are in excess of 1650°C (3000°F). These temperatures are generally high enough that, given time, all of the coal ash would completely melt. By contrast, peak temperatures potentially achievable for the distributed mixing burner (DMB) and fuel rich fireball (FRB) are 1200°C (2200°F) and 1425°C (2600°F), respectively. At these reduced temperatures, especially the temperature reported for the DMB, less of the ash is likely to be molten. The result is that slagging in the furnace may decrease, perhaps substantially, depending on the ash melting characteristics. However, as discussed earlier, any flame impingement on furnace walls will cause localized reducing conditions and increased slagging.

Slagging may also be affected by the limestone particles injected into the furnace. These particles may interact with molten ash particles altering their melting characteristics. Calcined limestone particles consist primarily of CaO. Thus, if calcined limestone particles combine with molten ash particles in the furnace, the effect is to increase the proportion of basic constituents in the ash. Depending on the extent of interaction, this could lead to decreased fusion temperatures and increased slagging for bituminous type coals. On the other hand, it could lead to increased fusion temperatures and decreased slagging for many low rank coals.

Some example calculations are presented in Tables 9-6 and 9-7 for high and low sulfur coals showing the impact of limestone addition on ash composition and softening temperature. These calculations assume 100 percent calcination of the injected limestone and combination of the limestone and ash particles in proportion to their relative quantities. In other words, these calculations effectively represent the mixing of lime with coal ash in the laboratory and do not necessarily indicate what occurs in the furnace.

In Table 9-6 the ash softening temperature of a bituminous coal is shown to decrease as the quantity of limestone injected is increased, until a certain point is reached. After that point, the ash softening temperature increases with increasing limestone addition. However, with the subbituminous coal ash shown in Table 9-7, the softening temperature continually increases with increasing limestone addition. The important point to be recognized from these tables is that limestone injection may increase the slagging potential of bituminous type coals but probably will not for lower rank coals.

Thus, the influence of limestone injection on the coal slagging potential is dependent on the coal type and the degree of interaction between the calcined limestone and ash particles. This degree of interaction is a big unknown. It is likely influenced by the relative quantities of limestone and ash, the temperatures under which they are mixed, and the ash melting characteristics prior to limestone injection.

TABLE 9-6. EFFECT OF LIMESTONE INJECTION ON THE ASH COMPOSITION AND SOFTENING TEMPERATURE OF A BITUMINOUS COAL[a,b]

Coal: Illinois Bituminous - 4.0% S, 16.0% ash or 320 lb ash/ton coal

Injected Limestone						
Ca/S	0	0.5	1	2	3	4
lb LS/ton coal	0	148	296	591	887	1182
lb calcined solids/ ton coal	0	76.8	154	307	461	615
Analysis, wt. %						
SiO_2	48.2	39.5	33.7	26.3	21.8	18.8
Al_2O_3	24.9	20.6	17.7	14.0	11.8	10.3
Fe_2O_3	14.9	12.2	10.4	8.1	6.7	5.7
TiO_2	1.1	0.9	0.7	0.6	0.4	0.4
CaO	6.6	23.0	34.0	48.0	56.5	62.2
MgO	1.7	1.7	1.7	1.7	1.7	1.7
Na_2O	1.2	1.0	0.8	0.6	0.5	0.4
K_2O	1.5	1.2	1.0	0.8	0.6	0.5
B/A ratio[c]	0.35	0.64	0.92	1.4	1.9	2.4
Fe_2O_3/CaO	2.3	0.53	0.31	0.17	0.12	0.09
Calculated softening[d] temperature, °C	1241	1176	1218	1321	1406	1472
°F	2266	2149	2224	2409	2563	2681

[a] Multiply lb/ton coal by 0.5 to get kg/Mg coal.

[b] These calculations presume 100 percent calcination and complete mixing of ash and limestone.

[c] Base/acid ratio defined as $\frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2}$

[d] Softening temperatures were calculated using a correlation for bituminous and lignite coals presented in reference 3.

TABLE 9-7. EFFECT OF LIMESTONE INJECTION ON THE ASH COMPOSITION AND SOFTENING TEMPERATURE OF A SUBBITUMINOUS COAL[a,b]

Coal: Montana Subbituminous - 0.6% S, 9.0% ash or 180 lb ash/ton coal

Injected Limestone					
Ca/S	0	1	2	3	4
lb LS/ton coal	0	44.3	88.7	133	177
lb calcined solids/ ton coal	0	23.0	46.1	69.2	92.0
Analysis, wt. %					
SiO_2	36.0	32.3	29.4	27.0	25.0
Al_2O_3	19.0	17.2	15.7	14.5	13.5
Fe_2O_3	7.9	7.1	6.5	6.0	5.6
TiO_2	0.7	0.6	0.6	0.5	0.5
P_2O_5	0.3	0.3	0.2	0.2	0.2
CaO	15.8	24.3	31.1	36.6	41.2
MgO	4.5	4.2	3.9	3.7	3.6
Na_2O	1.7	1.5	1.4	1.2	1.1
K_2O	0.4	0.4	0.3	0.3	0.3
SO_3	13.6	12.1	10.8	9.8	9.0
B/A ratio[c]	0.55	0.75	0.95	1.15	1.33
Fe_2O_3/CaO	0.50	0.29	0.21	0.16	0.14
Calculated softening[d] temperature, °C	1159	1232	1277	1304	1323
°F	2119	2249	2331	2380	2413

[a] Multiply lb/ton coal by 0.5 to get kg/Mg coal.

[b] These calculations presume 100 percent calcination and complete mixing of ash and limestone.

[c] Base/acid ratio defined as $\frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2}$

[d] Softening temperatures were calculated using a correlation for lignite supplemented by additives presented in reference 3.

There is good reason to believe that the limestone and ash particles will not combine in the furnace in the same proportions as their relative quantities would indicate. In fact, there may be very little interaction at all if the limestone is injected at sufficiently low temperatures that the ash is already mostly solidified. Previous research studies[4] have indicated that limestone "deadburning" with resulting loss of reactivity occurs at solids temperatures above 1200°C (2200°F). Most coal ash is completely solidified by the time it cools to about 1090°C (2000°F) and is at least partially solidified at 1200°C (2200°F). Therefore, limestone injected at temperatures below 1200°C (2200°F) may not combine to a great extent with the coal ash particles, depending on the particular coal ash melting characteristics. At higher temperatures the combination is likely to be greater.

If slagging does substantially increase as a result of LIMB, special operating procedures may be required to control it, such as reducing boiler load, increasing sootblowing, or increasing excess air in the furnace. A substantial decrease in slagging due to LIMB may also require special operating procedures to control furnace heat absorption as previously discussed.

Ash Removal Impacts--

The impacts of LIMB on the furnace bottom ash removal system are not likely to be severe for dry bottom units. Conceivably, the total ash collected may increase slightly due to the greatly increased solids load in the furnace. However, previous test data[5] have indicated that almost all of the injected limestone leaves the furnace as fly ash.

The impacts may be severe for existing wet bottom or slag tap pulverized coal units. These units depend on maintaining the bottom ash in a fluid state. Limestone injection could help or hinder this process depending on coal type and the degree of interaction between the limestone and slag. However, probably even more important than limestone-ash interactions are the reduced flame temperatures currently envisioned for LIMB. These lower temperatures would probably increase the slag viscosity preventing it from being tapped.

Convection Section Operation Impacts

Convection section operation impacts associated with LIMB result primarily from limestone injection. The primary areas of concern are the potential impacts on fouling, erosion, corrosion, and ash removal. An additional area of concern, impacts on the overall boiler system heat transfer profile, was discussed under furnace impacts.

Fouling--

The impact of LIMB on fouling is expected to result primarily from the increased quantity of entrained solids in the combustion gases and the influence of these solids on deposit buildup. Also, any gas temperature changes in the convection section or large change in ash fusion properties will affect fouling.

Calcium is not a volatile compound and is not generally bad in terms of contributing to convection pass fouling. In fact, limestone injection has been used in pilot- and full-scale experiments carried out by DOE[6] to reduce the severity of fouling in high sodium low rank coals. Most of their recent experiments have involved pulsed additions of limestone so as to minimize the total quantities injected. This is considered more economically attractive for fouling control than continuous injection. However, some of their earlier work also included continuous injection.

The results indicated that the injected limestone apparently affected the surface properties of the deposited material interfering with the bonding process. While the ash deposition rate was not reduced the deposit strength was. Reduced deposit strength increases the effectiveness of sootblowers. Reduced deposit strengths resulting from injection of limestone or dolomite were also measured in some pilot-scale tests with bituminous coal conducted by Babcock and Wilcox.[7]

A potential problem, however, is that aside from the influence on deposit bonding, limestone injection greatly increases the total flue gas solids loading for high sulfur coals. For many bituminous coals limestone injection will easily double or triple the flue gas solids loading. In some units with tight convection pass spacings, this increased loading together with lowered ash fusion temperatures could lead to rapid deposit buildup beyond the control of existing sootblowing capability. This would cause ash bridging blocking flue gas passages. Rapid deposit buildup and plugging of the reheater was seen by TVA[8] in limestone injection tests with a medium sulfur bituminous coal. The reheater, in this case, had tube spacing clearances of only 2.5 cm (1 inch).

The existing units most likely to have tight spacings are those designed for high rank low fouling coals. Although physical data are not available, it is suspected that convection pass designs follow the same trends as furnace designs. Units designed in the 1960s are probably less conservative (have tighter tube spacings) and more susceptible to fouling problems than are current designs.

LIMB may also increase fouling if convection pass temperatures are raised or the limestone significantly reduces the ash fusion temperatures. In fact, these factors could work in conjunction. Lower fusion temperatures can increase furnace slagging which reduces furnace heat absorption and increases gas temperatures to the convection section. Any ash particles reaching the convection section in a softened state are likely to stick on available surfaces and increase fouling.

Erosion--

The increased masses of entrained particles resulting from limestone injection are likely to increase tube erosion somewhat. Increased erosion will probably be most noticable in those areas already most subject to erosion, such as the economizer. Also it is most likely to occur in those units requiring the highest limestone injection rates - units firing high sulfur coal.

Data are not currently available to assess the erosion rate impacts associated with limestone injection. One encouraging note is that most limestones do not contain large quantities of those species thought to contribute most to erosion - SiO_2 and Fe_2O_3. Any large increases in erosion rate may require installation of tube shields or reductions in boiler load to decrease flue gas velocities.

Corrosion--

Limestone injection results in a beneficial corrosion impact in the cooler portion of the convection section. Previous limestone injection experience[9,10] has indicated that the alkaline solids effectively remove most of the SO_3 from the flue gas. The result is to reduce the acid dewpoint thereby minimizing problems with acid mist formation and its resulting corrosive effects. This beneficial impact is expected to be most noticable in units firing high sulfur coals.

This earlier experience also indicated reductions in high temperature corrosion in the superheater sections. However, any flame impingement on the furnace walls from low NO_x burners would increase corrosion.

Ash Removal--

The large increase in solids entrained by the flue gas will likely impact the operation of the ash removal systems associated with the economizer and air heater. This increase in the flue gas particulate loading will also increase the solids loads handled by these removal systems. This could be a problem for existing units if they lack sufficient excess ash removal capacity to handle this load increase. This situation is most likely for systems firing high sulfur coals since greater limestone quantities are required for these systems.

Also, the high calcium and sulfate contents of the fly ash with LIMB will likely cause problems for existing units using wet sluicing systems. This ash will probably exhibit cementitious properties and therefore may cause plugging problems in the sluicing system. In fact, this was one of the major problems reported by TVA[11] in their tests with limestone injection. This problem is most likely to occur with older units firing bituminous coals. Sluicing systems are not as common in new installations as in older ones. In addition, the high calcium content of most lower rank coals reduced the number of applications of wet sluicing systems for economizer ash.

EFFECTS OF BOILER DESIGN ON PERFORMANCE OF LIMB

EPA has ongoing various bench- and pilot-scale studies to evaluate the influence of different variables on the SO_x/NO_x control performance of LIMB. The results of these studies will be presented in other reports prepared by the respective investigators. This report will not attempt to develop any conclusions based on these other studies. Instead it will present a few general observations on the effects of boiler design on variables likely to affect LIMB performance.

Two variables which are affected by boiler design may strongly influence the SO_x/NO_x control performance of LIMB. These are the time-temperature and reducing-oxidizing histories of the combustion gases as discussed below.

NO_x is known to be formed in two ways - oxidation of fuel bound nitrogen and thermal fixation of nitrogen present in the combustion air. NO_x formation is inhibited by maximizing fuel combustion under reducing conditions and minimizing gas temperatures which occur under oxidizing conditions. These principles form the basis of attempts to control NO_x formation by staged burner designs and other combustion modification techniques. The NO_x control performance of LIMB will likely be enhanced by those types of boilers or burners which can best utilize these principles.

The effects of the combustion gas history on the SO_x control performance of LIMB are less clear at the present time but will depend on the mechanism by which sulfur capture occurs.

The classical mechanism considered with conventional burners is the direct capture of sulfur dioxide by calcined limestone particles as shown below.

$$CaO + SO_2 + \frac{1}{2}O_2 \longrightarrow CaSO_4 \qquad (9\text{-}5)$$

As shown, this reaction requires oxidizing conditions. Equilibrium and kinetic considerations indicate that the most favorable temperature zone for this reaction is between 1200 and 870°C (2200-1600°F). In typical units, this temperature range corresponds to the cooler regions of the upper furnace and the high temperature portion of the convection section. Above this temperature range the limestone particles may undergo "deadburning" or a severe loss of reactivity. Below this range the sulfur capture reaction effectively ceases. Thus, with this mechanism the SO_x control performance of LIMB may be enhanced by those types of boilers or burners that maximize the residence time of limestone particles in this temperature zone.

EPA is also investigating the possibility that sulfur capture may occur under reducing conditions. An example mechanism is as follows.

$$CaCO_3 + H_2S \longrightarrow CaS + H_2O + CO_2 \qquad (9\text{-}6)$$

This type of mechanism may prove less sensitive to higher temperatures than sulfur capture under oxidizing conditions. With this type of mechanism the SO_x control performance of LIMB may be enhanced by those types of boilers or burners which maximize fuel combustion and gas residence times under reducing conditions.

The ongoing EPA research and development program is attempting to optimize burner designs and combustion conditions for various types of furnaces (i.e. tangential and wall fired units) to maximize NO_x and SO_x control. Depending on the relative successes of these efforts, LIMB may show enhanced performance with one type of furnace versus another.

If upper furnace residence time proves to be an important variable affecting SO_x control, then LIMB performance may be enhanced by those boilers with larger furnace residence times. As discussed earlier in the report, two variables influencing furnace residence times in existing units include the slagging/fouling tendencies of the design coal and the time period during which the unit was designed. Units designed for high slagging or fouling fuels generally have larger upper furnace residence times than other units. However, units designed during the 1960's generally have higher heat release rates (smaller furnaces) than other units.

If furnace residence time proves critical, then those units with short residence times may require derating to achieve good performance. Two other boiler operating procedures which can provide a direct means of control over furnace residence times and exit temperatures include burner tilt for tangentially fired boilers and flue gas recirculation.

In any case, the ongoing EPA effort should elucidate the final boiler design effects based on fundamental, pilot, and prototype studies.

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